CARBON RETENTION BY REDUCED-IMPACT LOGGING

By

MICHELLE AMY PINARD

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This dissertation is dedicated to John P. and Florence H. Pinard.

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Michelle Amy Pinard

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Global concern over rising atmospheric concentrations of carbon dioxide is stimulating development and implementation of policies aimed at reducing net greenhouse gas emissions by enhancing carbon sinks. One option for reducing net emissions is to lessen damage to residual forests during selective logging thereby retaining carbon in biomass. A pilot carbon offset project was initiated in Malaysia in 1992 in which a power company provided funds to a timber concessionaire to implement guidelines aimed at reducing logging damage; in doing so, the utility gained potential credit towards future emissions reduction requirements. To quantify the reduction in soil disturbance resulting from the implementation of harvesting guidelines, I measured soil disturbance associated with ground-skidding in the two areas. To quantify the carbon retained due to this effort, I compared the biomass both before and after logging of dipterocarp forests logged according to reduced-impact logging guidelines with forests logged by conventional methods.

Prior to logging, the forest stored approximately 400 Mg biomass ha^{-1}. High volumes of timber were removed from both logging areas ($mean_{CNV} = 154$, $mean_{RIL} = 109\ m^3\ ha^{-1}$). About 17%

of the conventional logging area was covered by roads and skid trails; in contrast, 6% of the reduced-impact logging area was similarly damaged. Skid trails in reduced-impact logging areas were less severely damaged than those in conventional logging areas; the proportion of skid trails with subsoil disturbance was less than half that in conventional logging areas. Forty-one percent of the unharvested trees <60 cm dbh were severely damaged from logging in conventional logging areas in contrast to 15% in reduced-impact logging areas. One year post-harvest, reduced-impact logging areas held about 42 Mg C ha^{-1} more than conventional logging areas.

To investigate the consequences of reductions in logging damage for ecosystem carbon storage, I constructed a model to simulate changes in biomass and carbon pools following logging. Simulation results indicate that the relationship between fatal stand damage and ecosystem carbon storage is not linear and, at 50-60% fatal stand damage, biomass recovery following logging is severely limited. Reducing fatal damage from 40 to 20% is associated with a 20% increase in mean carbon storage over 60 years.

CHAPTER 1

THE REDUCED-IMPACT LOGGING PROJECT IN SABAH, MALAYSIA

Introduction

Uncontrolled logging and rising atmospheric concentrations of "greenhouse" gases are distinct problems with somewhat overlapping solutions. Many logging operations in the tropics involve unregulated and unsupervised selective cutting; though only a small proportion of the trees are harvested, a large proportion of the forest is damaged (*e.g.*, Fox 1968a; Uhl & Viera 1989; Johnson & Cabarle 1993). Without costly silvicultural interventions, heavily damaged residual forests yield little timber and thus are at high risk of conversion to other types of land use. Open canopies and heavy vine loads, typical of many heavily logged forests, increase forest vulnerability to fire and further degradation (*e.g.*, Uhl & Buschbacher 1985; Kauffman *et al.* 1988). Appropriate timber harvesting methods exist but incentives to implement better practices are lacking in many countries (Gillis & Repetto 1988). Policies aimed at reducing greenhouse gas emissions may provide a financial incentive for better logging.

In 1992, 52 nations signed a resolution to adopt policies to mitigate climate change by limiting emissions and enhancing greenhouse gas sinks and reservoirs (Framework Convention on Climate Change, UNCED 1992). The convention supported cost-effective approaches to reducing net emissions and recommended cooperation between nations such as in joint implementation programs that allow greenhouse gas emissions in one nation to be offset by reduced emissions or increased sequestration in another.

A wide range of opportunities exists for carbon offset programs in forestry. For example, estimates of the potential for carbon sequestration have been published for the following activities: preserving old growth forests (Harmon *et al.* 1990), controlling forest fires (Faeth *et al.* 1994), creating plantations and reforesting degraded lands (Sedjo 1989; Schroeder 1992), increasing rotation times in plantations (Cropper & Ewel 1987; Hoen & Solberg 1994) and reducing logging damage (Putz & Pinard 1993). Forestry-based offsets increase terrestrial carbon storage either by expanding forest cover or by maintaining or improving existing forest for carbon storage. This dissertation explores the potential for increasing carbon retention in managed forests by reducing avoidable logging damage. By improving harvesting practices, fewer trees are killed or damaged during logging and more carbon remains in the forest in living trees. Furthermore, if residual stands contain more trees of larger diameter than areas conventionally logged, future yields of timber are also likely be higher.

Scope of Dissertation

The objective of this dissertation is to explore the potential of reduced-impact logging for offsetting carbon emissions. My interests are principally with relevant ecological and biological processes and, consequently, my treatment of related political, economic, and silvicultural issues is superficial. The dissertation contains five chapters. This first chapter introduces the concept of reducing logging damage as a carbon offset, describes conventional logging practices in Sabah, and provides an overview of the harvesting guidelines upon which the Reduced-Impact Logging (RIL) Project is based.

Soil disturbance caused by yarding with bulldozers is the subject of the second chapter. After a comparison of soil disturbance associated with two logging systems, conventional and reduced-impact logging, I explore the importance of soil disturbance for forest recovery based on a

study of woody stem densities and species richness across a chronosequence of old skid trails and logged forest.

The third chapter details quantification of carbon retained in forest biomass due to implementation of harvesting guidelines. In this chapter, I describe forest biomass, above- and below-ground stores, before and after logging. I compare logging damage in forest logged by conventional methods and in forest logged according to RIL guidelines. Finally, I quantify the carbon retained in biomass due to implementation of the guidelines.

The simulation model of carbon dynamics in dipterocarp forest (Chapter 4) is intended to simulate forest recovery following disturbance by logging. I use the model as a tool for organizing information relevant to forest carbon storages and fluxes after logging. Simulation results are evaluated through a series of sensitivity analyses and comparisons to field observations and published data. I evaluate the effects of reductions in logging damage on forest carbon storage by examining output from simulations.

In the final chapter, I discuss several policy issues related to international carbon offset programs in forestry. I describe how the carbon retained due to the Reduced-Impact Logging Project might be valued and end with general conclusions about the suitability of reduced-impact logging as a carbon offset.

Conventional Logging Practices in Sabah

When commercial forests in Sabah are selectively logged (*e.g.*, Kleine & Heuveldop 1993), all mature trees (>60 cm dbh) of commercial species felled during the first harvest. Trees in the Dipterocarpaceae represent 90% of the total volume of commercial timber extracted (Sabah Forestry Department 1989). Sabah's silvicultural system is a modification of the Malayan Uniform System (Wan Razali 1993); seedlings and saplings present at the time of logging are assumed to replace the

mature trees in a 60 yr logging cycle. Pre- and post-logging inventories are carried out, but the data are not currently used to prescribe cutting limits or silvicultural treatments (Tang 1987). Tending of the residual potential or future crop trees through poison-girdling of overstory competitors, though initially part of the silviculture system, was discontinued because only about a third of the logged forest retained an overstory (Chai & Udarbe 1977).

In a typical logging operation in Sabah, logs are skidded to the roadside or log landing (flat, cleared area for storing logs) by bulldozers (a few high-lead cable yarding systems are also used). On average 8-15 trees are felled per ha, representing 50-120 m^3 of timber (Sabah Forestry Department 1989). Damage to the forest is extensive; as much as 30-40% of the area is traversed by bulldozers (Chai 1975; Jusoff 1991; Nussbaum *et al.* 1995), and 40-70% of the residual trees are damaged (Fox 1968a; Nicholson 1979). These relatively high levels of damage are due to both high timber volumes extracted and poor harvesting practices. Typically, little pre-harvest planning is carried out, and the activities of fellers and bulldozer operators are not well-coordinated.

Current forest management practices in Sabah are not sustainable because the volumes of timber extracted, the area logged each year, and damage to advanced regeneration are all too high (Sabah Forestry Department 1989). A new forest management system is clearly needed in Sabah and is presently under development by the Sabah Forestry Department (Kleine & Heuveldop 1993; Udarbe *et al.* 1994). As is true for many tropical countries, however, lack of forestry department staff and difficulties in enforcing regulations over large and dispersed tracts of forest can render even the best regulations ineffective (Jabil 1983). Programs that provide concession holders with incentives for better management practices may help stimulate change in the industry.

The Reduced-Impact Logging Project

In 1992, the Reduced-Impact Logging (RIL) Project was established between Innoprise Corporation, a timber concessionaire in Sabah, Malaysia, and New England Electric system, a coal-burning utility in Massachusetts, USA. New England Electric provided funds to Innoprise for training staff and implementing harvesting guidelines (Appendix A) aimed at reducing logging damage in 1400 ha of their concession (total concession area is ≈ 1 million ha with annual logging of about 20,000 ha). The carbon retained in the forest due to these efforts could be claimed by the utility as a carbon offset. Contemporary conventional selective logging practices in the area provide the baseline for comparison.

The 1400 ha experimental area dedicated to the project is divided between two commercial forest reserves in southeastern Sabah, a 450 ha tract in Ulu Segama Forest Reserve (5°0'N, 117°30'E, 150-750 m a.s.l.) and a 950 ha tract in Kalabakan Forest Reserve (4°25'N, 117°29'E, 150-900 m a.s.l.). This study is based on data from Ulu Segama only. The project began in May 1992 when woody vines were cut in Ulu Segama; logging is expected to be completed in the second tract, Kalabakan, by December 1995. The logging crews and forest rangers working in the experimental area were trained by foresters from the Queensland Forest Service and expert fellers from Sweden. The harvesting guidelines (Appendix A) were based on best management practices recommended in Indonesia, Malaysia, and Australia.

The harvesting guidelines developed and adopted by the Reduced-Impact Logging Project specify practices expected to reduce logging damage and thereby retain more carbon in living trees and promote post-logging biomass increments. The focus of the remainder of this chapter is the development and implementation of the Reduced-Impact Logging harvesting guidelines.

RIL Harvesting Guidelines

The reduced-impact logging guidelines were initially drafted from best management practices recommended by the Queensland Forest Service (Australia) and the Smartwood certification program of the Rainforest Alliance. The guidelines include specifications for pre-harvest planning, vine cutting, felling, skidding, and post-harvest site closure. During the project's first two years, the guidelines have been modified to increase operational efficiency and the guidelines' applicability to the forest conditions and soils in Sabah. Refinement of the guidelines involved input from field staff, an international advisory committee, environmental groups, and representatives of local state and private sector forestry institutions. In the following sections, the harvesting guidelines are outlined, and some of the issues that emerged during the first two years of implementation are described.

Planning

Knowledge of both the terrain and the distribution of harvestable timber is central to controlled selective logging. Topographic maps (1:50,000 scale) available for the RIL project area are unreliable and commercial trees are unevenly distributed. Therefore, pre-harvest planning calls for preparation of a 100% stock map (1:5,000 scale) of harvestable trees. The stock map also shows stream and road buffer zones and sensitive areas to be excluded from logging; the map forms the base for the harvest plan.

The value of these costly 100% stock maps was debated midway through the project. Costs of stock map preparation represented about 16% of the total cost of implementing the guidelines (about \$53 ha^{-1}). As illustrated in a concurrent research project in the area (Cedergren *et al.* 1994), without any prior knowledge of the terrain, trained rangers can locate trees to be felled on an ad hoc basis as they mark extraction routes based on a simple spacing rule that considers tree heights, winch cable lengths, and terrain. The rangers involved with the RIL project, however, argued that stock

maps are essential for proper planning. In the process of making the maps, they become intimately familiar with the forest and the timber resource. All subsequent aspects of the harvest plan are based on the stock map.

Efficiency of logging operations is greatly facilitated by sensible road routings, but prior to the RIL project, stock maps were not made, and road locations were consequently often suboptimal. Roads and skid trails generally are located on ridges to avoid steep grades, to facilitate uphill skidding, to minimize skidding distances and stream crossings, and to reduce the amount of sidecast soil entering streams. Main extraction routes and landing areas are located on the stock map and then these locations are checked in the field and marked with paint. The end points of all skid trails are also clearly marked.

Rangers mark trees to be felled with a record number and with a vertical paint blaze to indicate the intended direction of fall. Also, potential crop trees of good form and larger than 20 cm dbh are marked with a ring of blue paint if they are at risk of being damaged from felling or skidding. Tree enumeration and marking for directional felling were not done simultaneously during the pilot project, but combining these two activities will increase operational efficiency.

Vine Cutting

About one year prior to logging, all vines with stems > 2 cm dbh are cut. Figs are protected and no cutting is done in buffer zones. Vine-cutting reduces felling damage because the tree crowns are not tied together, and it reduces post-felling vine infestations because there are fewer fallen vine stems to resprout (Fox 1968a; Putz 1991). The effects of vine cutting on arboreal animals and forest biodiversity in general deserves attention from researchers but has not yet been addressed in the RIL Project.

The need to cut vines before logging is primarily a problem for tropical forestry. In our study area, density of woody vines > 2 cm dbh averaged 586 stems per hectare (SD = 211, N = 104

plots in 4 logging units, Chapter 3). The utility of vine cutting is debated, perhaps because the impacts of vine cutting on logging damage are not always obvious and the cost is substantial (about $US 25 per ha). Certainly part of the reduction in the number of trees uprooted during logging (a decrease from 37% of the residual trees in areas logged conventionally to 13% in areas logged according to the guidelines) is related to vine cutting. Several studies designed to measure the decrease in logging damage due to vine cutting in Malaysia reported a benefit (Fox 1968a; Liew 1973; Appanah & Putz 1983; Cedergren *et al.* 1994).

Tree Felling

Decisions about felling direction are based on feller safety, ease of skidding, avoidance of damage to harvested and potential crop trees, and minimizing impacts on buffer zones. Trees are felled and winched towards pre-marked skid trails. Directional felling reduces damage to potential crop trees and facilitates skidding both by avoiding the need to reorient logs and by shortening the overall extraction distance by up to the length of the log (up to 30 meters).

Recommended in the guidelines but not required is the use of plastic wedges during felling. Wedges give fellers added control and help fellers discern small changes in direction of lean as the tree is felled. Fellers working on the RIL project have not adopted the use of wedges and argue that plastic wedges are unnecessary and their required use actually places fellers at risk. When needed, fellers use wooden wedges made ad hoc at the tree to be felled.

Fellers consistently drop trees within 10 degrees of the marked direction (Project Records, unpubl. data). Success in directional felling of huge trees with eccentric crowns on steep slopes is impressive, but it should be pointed out that tree markers select the silviculturally optimal direction from what they judge to be the possible range. Furthermore, during the first year of the project, the number of harvestable trees felled in the experimental area was less in RIL areas than in comparable areas logged using conventional methods, perhaps in part due to more frequent rejection of trees by

fellers, uncertain of their ability to fell the tree in the direction indicated. More training would increase the skill and confidence of the fellers, thereby increasing the arc over which trees can be felled and reducing the number of harvestable trees left standing. During the pilot phase, rangers marked trees with the assistance of fellers because the rangers felt they had insufficient training to determine possible felling directions. This process, however, is subject to undo influence by fellers. Forest rangers need to be trained to so as to be able to select felling directions from the full range of technically possible directions.

Winching and Skidding

Bulldozers are destructive machines that were not designed for skidding logs, but their utility in logging heavily stocked primary dipterocarp forests cannot be ignored; in eastern Sabah, the average log weighs 7-9 tons, and 50-200 cubic meters of timber typically are harvested from each hectare. Under the RIL guidelines, main skid trails are constructed by logging crews following rangers' paint blazes. During extraction activities, bulldozers are restricted to these main trails. The guidelines call for extensive use of bulldozer-mounted winches to move logs from the stumps to main skid trails. The weight of the 32 mm cables, however, precludes winching over distances greater than about 15 meters. The use of a second small winch to pull out the heavy cable deserves investigation.

By restricting the practice of blading surface soil and sidecutting, the deleterious effects of skid trails are reduced. In the first 450 ha to be logged according to the RIL guidelines, skid trail area averaged 3.4% of the total area logged in contrast to 12% in adjacent areas logged by conventional methods (Chapter 2). Further, the percentage of the skid trails with subsoil exposed averaged 38% in the RIL areas in contrast to 87% in the conventionally logged areas. Many tropical soils are highly erodible; the presence of a litter layer on the soil surface can reduce soil erosion substantially (*e.g.,* Ross & Dykes 1993).

Skidding logs with bulldozers is difficult, dangerous, and particularly destructive on slopes greater than 15-20 degrees. In commercial forests elsewhere in the world, ground-based yarding is restricted to slopes less than 17 degrees (30%, *e.g.,* Dykstra 1994) because environmental damage increases greatly as slope increases (Brady 1984). The RIL project guidelines limit bulldozers to slopes less than 35 degrees (70%). Trees on slopes greater than 35 degrees can be felled only if they can be winched and skidded from a position on a slope 35 degrees or less. The 35 degree cut-off reflects a compromise between reducing soil damage and foregoing timber in a large portion of the remaining commercial forest in Sabah. For example, over 20% of the first parcel dedicated to the project (450 ha in Ulu Segama Forest Reserve) included slopes greater than or equal to 35 degrees; the net area inaccessible due to the slope restriction was even greater as some less steep areas were surrounded by steep areas. Consequently, the volume of timber removed from the first 450 ha reduced-impact logging area was possibly 20% less than what might have been extracted by conventional selective logging.

The issue of loss of timber harvested due to slope restrictions is the primary focus of current negotiations about the future of the project. Arguments are being made by the concessionaire that the slope restriction should be relaxed because overall damage to the forest can still be minimized by careful planning of skid trail locations, directional felling, etc. An underlying assumption in their argument is that damage to the soil is less important than damage to the residual stand. An alternative solution would be to combine aerial with bulldozer yarding. The current proposal for project expansion involves a combination of helicopter and bulldozer yarding and incorporates the higher extraction costs associated with helicopter system into the cost of the carbon offset. Where no incentive exists to protect the resource, the additional extraction costs associated with aerial yarding are difficult for the concessionaire to justify.

The restriction against wet weather skidding, although certainly important for minimizing soil damage (DeBonis 1986), slowed harvesting operations substantially in the RIL areas. The delays experienced by the contractors increased the overall costs of extraction. Though comparative financial assessments of selective logging in Sarawak, Malaysia (Marn & Jonkers 1981) and Suriname (Jonker 1987; Hendrison 1990) suggest that reduced-impact logging costs less per cubic meter of timber than conventional approaches, our experience with the RIL project in Sabah suggests that damage-controlled logging may cost more than conventional logging.

Logging Area Closure

After logging is completed in a 40-60 hectare unit, the skid trails are closed through installation of cross drains at specified intervals (*e.g.,* < 20 meters on slopes 15-20 degrees). The goal of the guidelines for skid trail marking, construction, use, and closure is to reduce overall damage to the forest. If erosion is minimized, the same skid trail network should be utilizable when the stands are logged in 30 to 60 years. Although the drain spacings recommended in the RIL guidelines seem fairly standard, the field staff has argued convincingly that on some skid trails, cross-drain construction would increase disturbance to soils. If surface soils are protected from blading and skid trails are properly located, installing drainage structures may not be justifiable on hydrological grounds. Inspection of skid trails on slopes of 15 - 20 degrees that were subjected to as many as 30 bulldozer passes and three months of heavy rains revealed no signs of gullying. Skid trails with an intact root mat and litter layer are uncommon in the conventionally logged areas (mean of 4 logging units = 1.6%), but they represent 12% of the skid trails in the RIL areas.

Training in Reduced-Impact Logging Techniques

Successful implementation of the reduced-impact logging guidelines depends on substantial technical expertise on the part of sawyers, bulldozer operators, and forest rangers. Traditionally,

Malaysian forest rangers are trained in mensuration and inventory methods, but their familiarity with harvesting techniques is limited. Sawyers and bulldozer drivers receive no explicit training but apprentice for several years before becoming operators. The Reduced-Impact Logging Project sponsored training for representatives of several levels in the forest management hierarchy. One of the first project activities was a visit by senior Innoprise staff and logging contractors to areas managed by the Queensland Forest Service. Although it would have been better to have visited an actively managed forest, seeing one that had been carefully logged was nonetheless valuable. Several of the Australian foresters who hosted the ICSB visit then came to Sabah as advisors in implementing the reduced-impact logging guidelines. Ten tractor drivers and fifteen ICSB field staff worked with three experienced Australian foresters for three weeks. During this training period, timber in a logging block of approximately 50 hectares was harvested.

Sawyers were trained by a Swedish specialist in directional felling during two 5-day training programs. Although these programs undoubtedly increased the fellers' abilities to direct the fall of trees, more training is clearly needed. Furthermore, forest rangers need to be trained so as to be able to select felling directions from the full range of technically possible directions. These rangers may themselves serve as future instructors, a situation from which considerable advantage will derive in regard to effectiveness, cost, and ease of implementation.

The people most responsible for success of the Reduced-Impact Logging Project are the Innoprise forest rangers, most of whom are high school graduates with one year of formal forestry training. The rangers supervise and participate in stock mapping, vine cutting, tree marking for directional felling, and skid trail planning, construction, use, and closure.

Monitoring Damage

Compliance with the reduced-impact logging guidelines and verification of reductions in logging damage are assessed by an independent team consisting of three foresters, one appointee of New England Electric systems (a representative from Rainforest Alliance), one appointee of Innoprise Corporation (a representative from the Forest Research Institute Malaysia), and one joint appointee (a representative from the Department of Forestry, University of Florida). The team, referred to as the Environmental Audit Committee, conducts 5-10 day site inspections twice per year. During these inspections, the team walks through the logging area and evaluates adherence to the guidelines and levels of logging damage. Also, the Committee meets with the field staff, loggers, and researchers responsible for logging damage studies and the carbon calculations for the offset due to reduced-impact logging. The Committee's involvement is anticipated to increase the project's international credibility, critical for qualification as a carbon offset. The rangers' records of logging damage provide data for monitoring the contractor's performance and for verifying compliance with the guidelines. The data provided in this dissertation also provide baseline data for carbon offset calculations.

The Cost of Reducing Logging Damage

As mentioned earlier, operational delays due to wet weather shut-downs increase extraction costs. Also, as compared with conventional practices, felling times are slower when following the RIL guidelines due to time spent marking and preparing trees for felling (Chua 1986a; Tay unpubl. data). The additional planning, mapping, and monitoring activities also increase extraction costs as compared to the conventional method.

Conversely, bulldozer maintenance costs are low in controlled logging sites, presumably because of less side-cutting and blading, because the steep, rocky areas are avoided, and because the

total length of skid trails constructed is much reduced. Also, total skidding time is less when following the RIL guidelines due to shorter skidding routes and less search time (Chua 1986b; Tay unpubl. data). The denser stocking of potential crop trees in areas with reduced logging damage eliminates the need for costly rehabilitation with enrichment planting and shortens felling cycles. It is still too early to provide a comprehensive view of the costs and benefits of the project, but an economic analysis is underway.

Discussion

While reducing logging damage does not guarantee sustainability, it is a general prerequisite for good management of selectively logged forest. Managing a forest sustainably makes economic and ecological sense for long-term concession holders that want to stay in the timber business, but the appropriate financial incentives seem to be lacking. More effective appear the incentives for conversion of logged-over forest to non-forest uses (*e.g.,* oil palm plantations). Management decrees initiated by forestry departments, though frequently based on sound management principles, are often rendered ineffective due to a lack of enforcement capacity. For example, in the Forestry Department in Sabah one professional forester is employed per 93,000 hectares of commercial forest reserve (Sabah Forest Department 1989).

Alternatives to bulldozer yarding on steep slopes need to be developed that are acceptable to local loggers. For example, demonstration of successful, commercial operation of skyline yarding systems in selectively logged tropical forests would help establish the viability of this method. Training in designing, rigging, and operating skyline systems is also needed.

Though the RIL Project has received accolades in the press (*e.g.*, Miller 1994), expansion of reduced-impact logging carbon offset projects is predicated on acceptance of the concept of joint implementation in both developed and developing countries. Several developing countries are

outspoken against some types of cooperative programs to abate climate change and are suspicious of the motivations of developed countries. Furthermore, if developing countries that are signatories of the Global Convention of Climate Change sell their inexpensive carbon offsets to outsiders, they will be left trying to satisfy the terms of the Convention with more costly offsets such as radically modifying their power-generating and fuel-consuming industries.

Alternately, if foreign utilities can produce appropriate financial incentives, concession holders may be tempted to endure outside assessments of their forest management. Carbon offset money could absorb the operational costs associated with altering harvesting systems and decreasing extraction rates. A reduction in extraction rate associated with adoption of better harvesting practices will move concessionaires toward sustainability and closer to qualification for timber eco-certification. Once sustainability is within reach, the profit margin and other advantages of certified timber may drive concessionaires further toward better management practices.

CHAPTER 2

SOIL DISTURBANCE RESULTING FROM BULLDOZER-YARDING OF LOGS AND POST-LOGGING FOREST RECOVERY ON SKID TRAILS

Introduction

In East Malaysia, though only 8-15 trees are extracted per ha, typically 15-40% of the area is traversed by bulldozer paths (Chai 1975; Jusoff 1991; Nussbaum *et al.* 1995). There are alternative harvesting systems that cause less soil disturbance, for example skyline (Miller & Sirois 1986) or helicopter (Blakeney 1992) yarding, but these techniques are generally more expensive than ground skidding on all but the most difficult terrain (*e.g.,* Aulerich *et al.* 1974). One of the goals of the Reduced-Impact Logging Project in Sabah was to reduce the area with soil disturbance while using existing equipment and personnel; bulldozer and chain saw operators were trained in damage-control techniques and harvesting guidelines were implemented in 1400 ha of dipterocarp forest (Chapter 1; Pinard *et al.* 1995). In this chapter, I compare soil disturbance associated with ground skidding in areas logged using conventional and reduced-impact logging techniques. To explore the importance of minimizing damage to soils for forest recovery, I examine tree regeneration on abandoned skid trails.

In the process of extracting logs from the forest with bulldozers, soil is disturbed in a number of ways that affect forest recovery. First, topsoils are displaced by the bulldozer blade during skid trail construction; displaced soil (hereafter, sidecast soil) is dispersed over slopes or forms linear mounds along the edges of skid trails. Although total soil organic matter content may not change across the entire logged area, its distribution does (Johnson *et al.* 1991), with bulldozed

areas losing, and sidecast mounds accumulating, soil organic matter (Gillman *et al.* 1985; Rab 1994). These localized losses in organic matter can have substantial effects on soil fertility (Gillman *et al.* 1985; Zabowski *et al.* 1994) and tree seedling growth and survival (Nussbaum *et al.* 1995; Woodward 1995).

During ground-based log yarding operations, subsoils are exposed and churned by the tracks of the bulldozer. Soil losses from these denuded areas can be substantial (*e.g.*, Hornbeck & Reinhart 1964; Ross *et al.* 1990). A hydrological study of recently logged dipterocarp forests in Sabah, Malaysia, documented stream sediment loads 14 and 2.5 times that of a nearby unlogged catchment during the first and second year after logging, respectively (Douglas *et al.* 1993); eroding roads and gullied skid trails were identified as the principal sources of post-logging sediment. Installation of proper drainage structures on skid trails, roads, and landings can reduce erosion substantially (Stuart & Carr 1991; Wenger 1984).

Soil structure is also damaged due to compaction from loads applied by bulldozers and logs skidded across the forest floor. As soils are compacted, soil porosity decreases, often causing decreased water infiltration and increased surface runoff, as well as decreased soil moisture availability, aeration and rooting space (Greacen & Sands 1980; Malmer & Grip 1990). During heavy rains, seeds and seedlings may be washed away (Borhan *et al.* 1987; Pinard *et al.* 1996). Soil bulk density values recorded in many post-logging habitats are within the range of values that negatively affect tree growth (Greacen & Sands 1980; Rab 1994). In some forests, changes in soil physical properties due to logging are apparent decades after logging (Congdon & Herbohn 1993; Van der Plas & Bruijnzeel 1993).

The extent and degree of soil disturbance associated with bulldozer yarding are variable and appear to be related to slope (Dyrness 1965; Stuart & Carr 1991), soil texture (Daddow & Warrington 1983 in Clayton 1990; Jusoff 1992), and soil moisture content at the time of logging

(DeBonis 1986; Jusoff 1992). Certain logging practices also influence soil damage, for example, size of logs extracted (Dickerson 1968) and extent of bulldozer blade use (Miller & Sirois 1986). Pre-harvest planning can increase the efficiency of log extraction and reduce the area damaged (Froehlich *et al.* 1981). Prohibiting wet weather skidding, skidding on steep slopes, and use of the bulldozer's blade can reduce further soil damage associated with logging.

To describe the reduction in soil damage achieved in the Reduced-Impact Logging (RIL) Project area, I compared areas logged using conventional and RIL techniques in terms of extent and degree of soil disturbance. To better understand the impacts of soil damage for forest recovery, I studied a series of skid trails in areas logged using conventional methods in 1976, 1988, and 1991.

Short-term studies of pioneer tree establishment on skid trails and log landings suggest that, during the first year after logging, tree establishment is limited by unfavorable site conditions, not by seed availability (Pinard *et al.* 1996). Herbivore damage and trampling of tree seedlings on skid trails are also commonly observed (pers. obs.; Moura-Costa & Lundoh unpubl. data). If skid trails are unfavorable for tree regeneration, I expect sapling densities to be lower on skid trails than in adjacent residual forest. If site conditions on skid trails become more favorable for tree establishment over time, I expect that sapling densities on older skid trails would be more similar to those in adjacent residual forest than those on younger skid trails.

Methods

Study Site

The study was conducted within the Yayasan Sabah concession in Ulu Segama Forest Reserve (5°0'N, 117°30'E, 150-750 m a.s.l.). Prior to logging, the tall, diverse forest is dominated by dipterocarps (see Chapter 3 for more details). Soils are orthic acrisols, nutrient rich in the upper 5 cm then dropping steadily in concentration through the soil profile (Nussbaum 1995); the upper

horizons have a loamy texture and are well-drained. The conventional timber harvesting system used in Sabah, as well as the harvesting guidelines being followed in Reduced-Impact Logging (RIL) areas, are described in detail in Chapters 1 and 3 of this dissertation. The key differences between the two systems are as follows: 1) RIL follows a pre-harvest plan with locations of all skid trails identified on a stock map of trees to be harvested, whereas conventional logging involves little or no pre-harvesting skid trail planning; 2) RIL restricts bulldozers to slopes <35 degrees, whereas conventional logging has no slope restriction; and 3) RIL restricts bulldozer blade use and encourages the use of the winch cable, whereas conventional logging does neither.

Soil Disturbance

To determine the extent and severity of soil disturbance associated with logging I mapped, measured, and classified all soil disturbance associated with bulldozer activity in eight logging units (approximately 50 ha each). Four units were selected randomly from a 450 ha experimental area logged according to the RIL guidelines by trained crews and closely supervised by forest rangers. For comparison, four units were selected randomly from an adjacent area logged by unsupervised and untrained crews using conventional methods.

I used three broad disturbance categories: 1) roads and log storage landings; 2) bulldozer paths (skid trails); and, 3) areas covered by sidecast soils. Roads and log landings generally are leveled and graveled surfaces on subsoils. Skid trail surfaces are variable and were further classified by degree of soil disturbance as follows: 1) subsoil exposed, either by blading or heavy bulldozer churning; 2) churned but topsoil mixed with upper layers of subsoil; and, 3) compacted by bulldozer passing over area but relatively little mixing of topsoil with subsoil. In the eight logging units, 100% of the area was surveyed for soil disturbance caused by logging. I measured lengths and slopes of roads and skid trails by sections; a section was a length of road or skid trail that was relatively uniform in slope, width, and direction. Widths were measured every 10 to 15 m or, for more rapidly

changing sections, in the midpoint of each section. Contiguous areas of sidecast soils (*e.g.*, linear soil mounds or tips) were also measured; for large areas with sidecast soils adjacent to roads and skid trails I measured the average slope and distance to the end of each soil mound (or slide). No effort was made to measure areas crushed or scraped during the winching of logs to the skid trails. The area of disturbed soil was calculated based on net loggable area per subblock (defined in Chapter 3). *T*-tests performed on arcsine-transformed data were used to compare treatments.

Plant Regeneration on Skid Trails

To describe woody plant establishment on skid trails I sampled old skid trails in 1994 in three logging coupes (1991, 1988, and 1976). Within each logging coupe, skid trails were located in four logging units that were separated by at least 1 km. Main skid trails originating at log landings or roads were selected in all cases. Skid trails were easily located in all three logging coupes. Often, the edge of the skid trail was marked by an uneven soil surface, probably the result of side-cutting with the bulldozer blade.

In each logging unit, I established 10 sampling points at 20 m intervals along a skid trail with the first point located at a random distance (0-20 m) from the landing or road. At each sampling point, three 2x2 m plots were established, one in the center of skid trail, another at the edge of the skid trail, and a third 10 m into adjacent forest, following a line perpendicular to the skid trail. The width of the skid trail was measured from edge to edge. Random numbers were used to determine whether the edge and forest plots would be placed to the left or the right of the skid trail; edge plots did not include skid trail surfaces though often sidecast soil was included. Within each plot I recorded the following: canopy cover (above 1 m) using a spherical densiometer (Lemon 1957), number of woody stems (>1 m tall, <5 cm dbh), and number of species. Trees >5 cm dbh were not included in the samples because the plot size was too small to adequately sample their densities at this level of replication. All dipterocarps (*i.e.,* commercial species) and colonizing tree

species (*e.g.*, *Macaranga* spp.) were noted as such. For plots on the surface of the skid trail, 1 subplot (1 m^2) was randomly selected for determination of above- and below-ground biomass. All vegetation was clipped at ground level, weighed, and subsampled for dry weight determination. Coarse roots (>5 mm diameter) were collected from a 50 x 50 x 50 cm pit located in center of subplot; roots were washed, and live and dead roots were separated, weighed and subsampled for dry weight determination.

For all analyses, logging units were considered replicates, and the plots within each unit were considered samples. Analysis of variance followed by Tukey multiple comparisons was used to compare stem densities, species richness, and canopy cover among the three logging coupes and the three habitats within each coupe. To compare skid trail width and biomass in skid trails in the three logging coupes, Kruskal-Wallis tests were used, followed by Tukey-type nonparametric multiple comparisons (Zar 1984). In all cases, the significance level used to reject the null hypothesis was 0.05.

Results

Soil Disturbance

A greater area of soil was disturbed in conventional units than in RIL units (t = 5.6, df = 6, P = 0.001; Fig. 2-1; Table 2-1). Road area was similar in the two treatments (t = 1.04, df = 6, P = 0.34), but skid trail area was much less in the RIL units than in conventional units (t = 4.95, df = 6, P = 0.003). Including only logged areas, mean skid trail density was much higher in conventional units (mean = 199 m ha^{-1}, SD = 35.8) than in RIL units (mean = 66.5 m ha^{-1}, SD = 25.7; t = 6.0, df = 6, P < 0.001).

Total volume of timber extracted per logging unit was not statistically different between the two methods (t = 1.88, df = 6, P = 0.11; Fig. 2-2); however, high variability and low replication limit

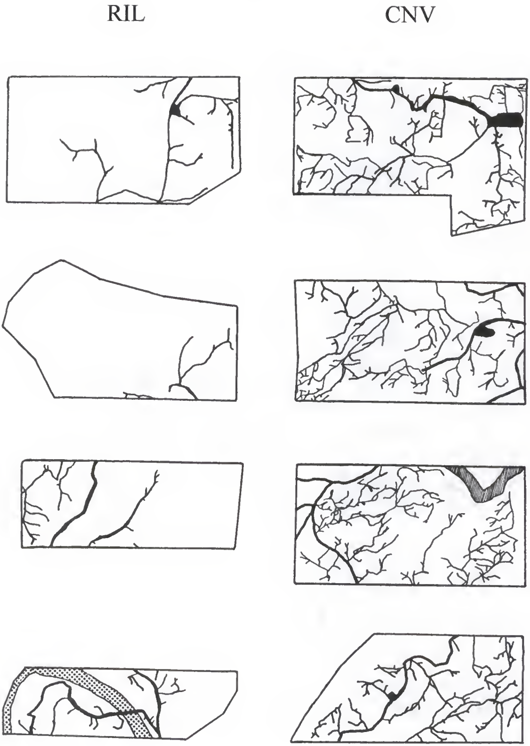


Figure 2-1. Diagrams of the eight logging units in which soil disturbance was measured. (CNV = conventional logging areas, RIL = reduced-impact logging areas). Thick black lines represent roads, thin black lines are skid trails, blackened areas are log landings, stipled areas are riparian zones, and the hatched area is a landslide below a road.

Table 2-1. Soil disturbance in conventional and reduced-impact logging units (100% area); $N =$ 4 per treatment. Skid trail area includes area covered with sidecast soil. Values are mean percentages (SD) of logged areas.

	Conventional Logging Units	Reduced-Impact Logging Units
Total Area Disturbed (%)***	16.6% (2.3)	6.8% (2.6)
Roads and Landings (%)	4.7% (0.8)	3.3% (2.5)
Skid Trails (%)***	11.9% (2.7)	3.5% (2.1)

*** $P < 0.01$

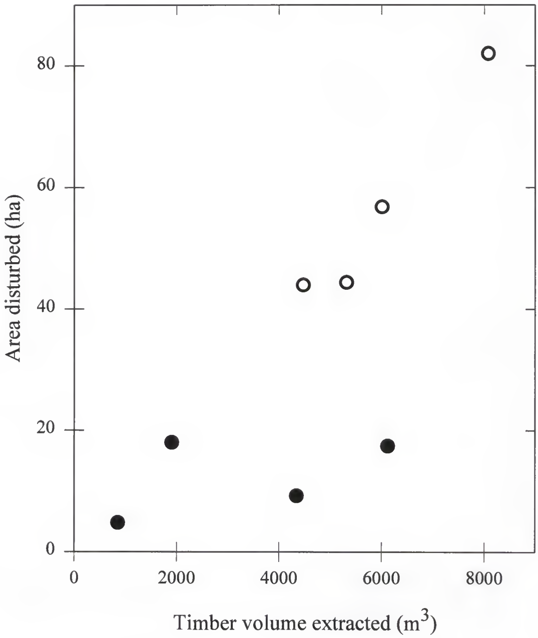


Figure 2-2. Total skid trail area (ha per logging unit) related to timber volume extracted (m^3 per logging unit) for reduced-impact logging areas (solid circles) and conventional logging areas (open circles).

the power of this analysis. Excluding unlogged sections within units, mean volume extracted was 136 m^3 ha^{-1} (SD = 29) in conventional units and 92 m^3 ha^{-1} (SD = 40) in reduced-impact logging units (Pacific Hardwoods Sdn Bhd, unpubl. data). Skid trail area (including sidecast mounds) per timber volume extracted was greater in conventional units (mean = 8.8 m^2 m^{-3}, SD = 0.56) than in RIL units (mean = 4.6 m^2 m^{-3}, SD = 3.04; U = 15, df = 1, P = 0.04). Including road area, soil disturbance per harvested tree was 140 m^2 $tree^{-1}$ (SD =16) in conventional and 94 m^2 $tree^{-1}$ (SD = 28) in reduced-impact logging areas. Skid trail disturbance was positively correlated with volume extracted for conventional units (Pearson Correlation Coefficient = 0.97, P = 0.03) but not for RIL units (Pearson Correlation Coefficient = 0.53, P = 0.54).

Within the area disturbed by skid trails, the severity of disturbance to the soil was greater in conventional than in RIL logging units (Table 2-2). Skid trails with a bladed surface (or sidecut) were predominant in the conventional units (mean = 87.2%, SD = 5.6%) whereas only 38% (SD = 9.9%) of the skid trails in the RIL units had a bladed surface. The most common surface condition for skid trails in the RIL units was churned (*i.e.*, the topsoil remaining in place but being mixed with the upper layer of subsoil; Table 2-2). Skid trails with intact topsoil and litter layer were very uncommon in conventional logging units but covered about 12% of the skid trail surfaces in RIL units. In these compacted areas, saplings and vines resprouted soon after logging.

Plant Regeneration on Skid Trails

The width of skid trails surveyed in the three logging coupes ranged from 3.9 m to 6.0 m; mean width in the '91 coupe ($mean_{91}$ = 5.4 m, SD_{91} = 0.7) was greater than that in the '88 and '76 coupes ($mean_{88}$ = 4.1 m, SD_{88} = 0.2; $mean_{76}$ = 3.9 m, SD_{76} = 0.2; F =13.2, df = 2,9 P = 0.002; Tukey's Test P < 0.05). Both skid trail and forest habitats in the two older logging coupes had nearly closed canopies at the time of sampling (Table 2-3). Skid trail tracks in the '91 coupe, had more open canopies than edges or adjacent forest plots. For all three logging coupes, species

Table 2-2. Types of soil disturbance recorded in conventional and reduced-impact logging units ($N = 4$ per treatment) presented as mean percentage (SD) of total area logged.

	Conventional Logging Units	Reduced-Impact Logging Units
Area With Sidecast Soil(%)***	2.1% (0.2)	0.4% (0.5)
Skid Trail Surface Area (%)***	9.9% (2.7)	3.2% (1.6)
Bladed (%) ***	87.2% (5.6)	37.7% (9.9)
Churned (%) ***	11.1% (4.9)	50.2% (7.3)
Compacted (%) *	1.6% (1.1)	12.1% (9.5)

* $0.1 < P < 0.05$
*** $P < 0.01$

Table 2-3. Characteristics of vegetation in 1994 on skid trail tracks, skid trail edges, and adjacent forest in three logging coupes. Species richness refers to all woody stems >1 m tall and <5 cm dbh. All values are means (SD) per plot for four logging units, each unit with 10 sampling plots (2 x 2 m). Different superscripted letters within a row denote a significant difference (*P* < 0.05) between habitats within a coupe using Tukey multiple comparisons following ANOVA.

	Coupe	Skid Trail Track	Skid Trail Edge	Forest
Canopy Cover	'91	66% (14)^a	83% (3)^b	89% (2)^b
	'88	90% (3)^a	92% (4)^a	94% (2)^a
	'76	93% (2)^b	90% (2)^a	93% (2)^b
Species Richness	'91	1.8 (1.1)^a	5.5 (2.2)^b	7.0 (0.7)^b
	'88	1.1 (0.1)^a	3.8 (1.1)^b	5.1 (1.0)^b
	'76	2.7 (0.9)^a	5.2 (1.0)^b	6.5 (1.0)^b

richness (woody plants >1 m tall, <5 cm dbh) was lower on skid trail tracks than in edge or adjacent forest habitat (Table 2-3).

Fewer saplings were found on skid trail tracks than on skid trail edges or adjacent forest in all three logging coupes (Table 2-4). The '91 and '76 logging coupes had identical mean sapling densities on skid trail tracks although variance was higher in the '91 coupe than in the '76 coupe (Table 2-4). Forest habitats in all three coupes had relatively few pioneer tree saplings. Pioneer tree saplings were relatively abundant on skid trails and edges in the '91 coupe. Edges in the '88 coupe had more pioneer saplings than either the skid trails or adjacent forest. In the '76 coupe, pioneer tree sapling density was similar in the three habitats.

Dipterocarp sapling density was less on skid trails than adjacent forest in the '76 and '91 coupes (Table 2-4). In the '88 coupe, the three habitats had similar densities of dipterocarp saplings. The observed densities of dipterocarp saplings on skid trail edges and in adjacent forest habitats were similar to densities recorded for unlogged forest (mean = 430 saplings ha^{-1}, SD = 158; 1993 coupe) though the diversity was quite low in the '76 coupe where *Hopea nervosa* was dominant.

Aboveground biomass on skid trail tracks was extremely low (1.1-2.2 Mg biomass ha^{-1}) and was similar for the three logging coupes ($KW = 1.5$, df = 2, $P = 0.47$; Table 2-5). Coarse root biomass under skid trails followed a general pattern of more biomass under older skid trails. Under skid trails in the '76 coupe, coarse root biomass was greater than it was under skid trails in the '91 coupe (Table 2-5; $q = 4.16$, $P < 0.05$). Coarse root biomass under skid trails in the '88 coupe was intermediate and not statistically different from either the '91 or '76 year old skid trails ($q_{91\ vs\ 88} = 2.08$, $P > 0.05$; $q_{76\ vs\ 88} = 2.08$, $P > 0.05$). Dead root mass under skid trails was much higher in the '91 coupe ($median_{91} = 6.6$ Mg necromass ha^{-1}, $N = 4$) than in either the '88 or '76 coupes ($median_{88} = 1.0$; $median_{76} = 0.6$, Table 2-5). Total coarse root mass was not different among the three logging coupes ($KW = 3.04$, df = 2, $P = 0.22$). Woody roots >15 mm diameter made up about 43%, 50%,

Table 2-4. Stem densities (>1 m tall, <5 cm dbh) in 1994 on skid trail tracks, skid trail edges, and adjacent forest in three logging coupes. All values are means (SD) per ha; densities were calculated from 4 m^2 plots, 10 sample plots per unit, four units per coupe. Different superscripted letters within a row denote a significant difference ($P < 0.05$) between habitats within a coupe using Tukey multiple comparisons following ANOVA. Similar results were obtained when habitats were compared using frequency data in contingency table analyses.

	Coupe	Skid Trail Track	Skid Trail Edge	Forest
# Saplings and Vines	'91	8,130 (4,880)^{a}	22,060 (8,670)^{b}	22,500 (2,280)^{b}
	'88	3,500 (710)^{a}	12,630 (3,350)^{b}	15,880 (2,950)^{b}
	'76	8,130 (2,070)^{a}	18,380 (1,830)^{b}	22,750 (4,410)^{b}
# Pioneer Tree Saplings	'91	2,630 (2,630)^{ab}	4,690 (2,100)^{a}	560 (800)^{b}
	'88	1,000 (890)^{b}	3,560 (970)^{a}	880 (720)^{b}
	'76	310 (320)^{a}	440 (720)^{a}	60 (130)^{a}
# Dipterocarp Saplings	'91	60 (130)^{a}	560 (560)^{ab}	810 (130)^{b}
	'88	130 (250)^{a}	250 (500)^{a}	310 (470)^{a}
	'76	0 (0)^{a}	440 (330)^{b}	1,560 (1,390)^{b}

Table 2-5. Above- and below-ground biomass and necromass for three ages of skid trails. Values are medians (Mg organic dry mass ha^{-1} with range noted parenthetically) for $N = 4$ logging units ($n = 10$ samples per unit). Different superscripted letters within rows denote a significant difference ($P < 0.05$) between ages in nonparametric pairwise comparisons.

	3 Year Old	6 Year Old	18 Year Old
Aboveground Biomass	2.2 (0.8- 7.9)^{a}	1.1 (0.5-1.7)^{a}	1.4 (0.8-1.6)^{a}
Living Coarse Roots	0.3 (0.0- 1.0)^{a}	1.7 (0.7-4.2)^{ab}	4.6 (2.2-7.6)^{b}
Dead Coarse Roots	6.6 (0.4-12.0)^{a}	1.0 (0.2-2.1)^{a}	0.6 (0.2-3.4)^{b}

and 69% of total living coarse roots under skid trails in the '91, '88, and '76 logging coupes, respectively.

Discussion

Soil Disturbance - Conventional versus Reduced-Impact Logging

In sites logged according to the RIL harvesting guidelines, proportionally less area of soil was disturbed than in sites logged by conventional methods. An inefficient layout of skid trails, typical of unplanned, unsupervised operations, was apparent in conventional logging areas. Skid trails in conventional logging units were often cross-linked and located within 10 m of each other, whereas, in general, skid trails in RIL units were widely spaced and evenly dispersed across the logged area. A time-motion study of skidding practices in the two treatment areas documented the higher level of efficiency of yarding in RIL operations as compared with conventional logging, 1.98 US\$ m^{-3} and 4.51 US\$ m^{-3}, respectively (J. Tay unpubl. data).

The harvesting guidelines adopted by the RIL project include specifications about road location and construction, but the road in the RIL pilot project area was constructed before adoption of the RIL guidelines by the concessionaire, compromising flexibility in locating skid trails. The road was positioned low on slopes; this location was suboptimal and often forced downhill skidding. There was no difference in road density for the two methods (Table 2-1), but the area covered by sidecast soils, associated with the road, was less in RIL areas than in conventional logging areas, even though the roads in RIL units were used for processing logs. This difference reflects the attitudes of the operators working in the two areas; bulldozer operators in RIL areas worked carefully and with the awareness that the project's goal was to reduce damage. The operators in conventional logging areas were not similarly motivated.

The extent of soil damage associated with conventional logging in this study (mean = 17%; range = 14-20%) was at the low end of the range of published values for unsupervised logging in Malaysia (*e.g.,* 43%, Fox 1968a; 17%, Borhan *et al.* 1987; 16%, Jusoff & Nik 1992; 30%, Nussbaum *et al.* in press) and was similar to values for operations in Suriname (14.5% and 16.0%, Hendrison 1990) and Indonesia (16%, Cannon *et al.* 1994). Skid trail area in RIL units was similar to values obtained with planned operations in Suriname (5-7%, Hendrison 1990) and Australia (5%, Crome *et al.* 1992). The large variation in values reported for dipterocarp forests in Sabah may be due to differences in sampling methods, biases towards roadside locations, or differences in local topographical conditions. I expect the results from this study are relatively free from sampling biases because soil disturbance associated with logging was measured in 100% of the area of the eight logging units.

In general, damage to the residual stand is positively correlated with timber volume extracted (Nicholson 1979). In this study, soil damage was positively associated with harvested volumes in conventional logging areas but not in reduced-impact logging areas (Fig. 2-2). If main skid trails are located to optimize efficiency of log extraction, bulldozers are restricted to main skid trails, and logs are winched from the forest to the skid trail, one might expect that, after the whole area was rendered accessible by the main skid trails, the proportion of area disturbed by logging would remain fairly constant, regardless of the number of trees removed.

Unfortunately few studies of soil damage associated with logging in tropical forests include information on the volume of timber extracted or express damage in terms of volume extracted. Failure to include information about logging intensity makes it difficult to compare sites. One exception is a study conducted in the Brazilian Amazon; Verissimo *et al.* (1992) found that 218 m^2 of ground surface was scraped by bulldozers (roads and skid trails) for each harvested tree. Comparable figures for this study are much lower ($mean_{CNV}$ = 140 m^2 $tree^{-1}$ and

mean $_{RIL}$ = 94 m^2 $tree^{-1}$), perhaps reflecting differences in the size of harvested trees and number extracted per hectare.

Skid trails in RIL units were, in general, less severely damaged than those in conventional logging units, the proportion of skid trails with subsoil disturbance was less than half that in the conventional logging areas. In part, this difference may be due to the fact that bulldozers did not traverse slopes >35 degrees in RIL areas, so may have been less likely to require the use of the blade. Blading is often considered essential on slopes >24 degrees to increase stability and control (Stuart & Carr 1991). But blading and side-cutting were not restricted to steep areas in the conventional logging units; ≈87% of the skid trails had exposed and disturbed subsoils. The skid trails receiving subsoil disturbance in RIL units (≈38%) were typically main skid trails that received heavy traffic. In conventional logging units, branch and main trails were not distinguishable in terms of soil damage class. The restriction on wet-weather skidding in RIL areas also probably contributed to the observed differences; in RIL units, all skid trails showing subsoil disturbance had been logged during the wetter season.

Plant Regeneration on Skid Trails

Fewer sapling and pole-sized trees were found on abandoned skid trail tracks than in adjacent, residual forest in '91, '88, and '76 logging coupes. This result suggests that, even 18 years after logging, tree regeneration on skid trails is less than that in residual forest. Tree regeneration on the edges of skid trails appears similar to that in adjacent forest in terms of sapling densities and species richness. However, species composition is different in the two habitats, with pioneer tree species being more common on skid trail edges than in residual forest.

Sapling densities in the '91 and '76 coupes are very similar, suggesting that conditions for tree regeneration on older skid trails are no better than those on younger skid trails. The similarity in biomass on skid trails from the three logging coupes also suggests little change. Immediately after

logging, 98% of the skid trail area in conventional logging units was bare of vegetation. The quantity of aboveground biomass on the 3-, 6-, and 18-year-old skid trails was only slightly higher than that recorded on one-year-old skid trails (0.3 Mg biomass ha^{-1}; SD = 0.38; Chapter 3). Living coarse root biomass appears to be increasing with time since logging, as one might expect, but at 18 years after logging, coarse root biomass was 12% of the pre-logging value observed elsewhere in the forest reserve (Chapter 3).

I interpret the results from this study with caution and recognize that pre-logging conditions in the three logging coupes studied may have differed. Nevertheless, I am fairly confident that all three areas were heavily logged (Pacific Hardwoods, unpubl. data) and that the coupes have not been re-entered by heavy equipment after the initial selective cut. I chose three different-aged logging coupes in order to look at the potential for recovery on skid trails over time, but comparisons among habitats within a coupe involve fewer assumptions than do comparisons across the three coupes.

I expected that if soil disturbance favors pioneer trees over more persistent species, then the density of pioneers on skid trails would be higher than in adjacent forest. This was supported by the data from the younger areas, the '91 and '88 coupes, where pioneer sapling densities on skid trail edges were higher than densities in adjacent forest. Densities on skid trail surfaces were not different from densities in forest plots. Perhaps pioneer tree densities in forest plots were high relative to undisturbed forest because of the inclusion of felling gaps, which may provide opportunities for pioneer tree establishment, in some of the plots. Also, few pioneer saplings would be expected to survive under the closed canopy observed in the '88 and '76 coupes.

Several studies in neotropical rain forest recorded vigorous tree seedling establishment along the edges of skid trails and roads (*e.g.*, Jonkers 1987; Verissimo *et al.* 1992; Guariguata & Dupuy 1995) two to three years after logging. It does not necessarily follow, however, that high densities of

saplings on skid trails will eventually develop into a stand of trees; unfavorable soil properties (*e.g.*, compaction and low nutrient status) may continue to limit tree growth on skid trails for many years.

I attribute lower densities of saplings on skid trails as compared with adjacent forest to unfavorable establishment conditions in those habitats. An alternative explanation for lower sapling densities on skid trails is that crowns and root systems of residual trees occupy these areas and the competition for resources on skid trails is greater than that in adjacent forest. Sapling densities in these sites may have been lower than in adjacent forest prior to skid trail construction. A manipulative study of tree establishment in these habitats that controlled for competition with neighboring trees would help to elucidate the mechanisms driving differences in sapling densities.

Conclusions

Implementation of harvesting guidelines in a ground-based yarding system substantially reduced the extent and degree of soil disturbance associated with logging. About 84% of the skid trail area in conventional logging areas had subsoil disturbance. Distribution patterns in biomass, species richness and sapling density across habitats in logged forest suggest that even 18 years after conventional logging, areas with soil disturbance are less productive than areas without. In reduced-impact logging areas, about 62% of skid trail area retained topsoil. Retention of organic matter in these compacted areas may result in improved plant regeneration (Woodward in press), but for many soils, most compaction associated with skidding happens with the first few passes of the bulldozer (Dias & Nortcliff 1985; Koger *et al.* 1985). If damage to soil structure is to be minimized, reducing the area traversed by bulldozers will be more important than reducing the traffic on any particular skid trail.

CHAPTER 3

RETAINING FOREST BIOMASS BY REDUCING LOGGING DAMAGE

A pilot carbon offset project, in which a power company provided funds to a timber concessionaire to implement guidelines aimed at reducing logging damage, was initiated in Malaysia in 1992; in doing so, the utility gained potential credit towards future emissions reduction requirements. To quantify the carbon retained due to this effort, dipterocarp forests logged according to reduced-impact logging guidelines were compared to forests logged by conventional methods, in terms of above- and below-ground biomass both before and after logging. This comparison is the focus of this chapter.

I have three objectives for this chapter. The first objective is to describe forest biomass stores both before and after logging. The second is to compare logging damage in forest logged by conventional methods and in forest logged according to reduced-impact logging harvesting guidelines. The third objective is to quantify the carbon retained in biomass due to implementation of the harvesting guidelines.

Study Site

The experimental area in Ulu Segama supports primary dipterocarp forest, spectacular both for its stature and its high density of big trees. Canopy height averages ≈45 m but emergent trees reach heights of 70 m. The terrain consists of series of steep ridges; over 75% of the area occurs on slopes exceeding 20° and generally <200-300 m long (Pinard, unpubl. data). Soils are varied but

primarily are Ultisols derived from Tertiary sediments (Ohta & Effendi 1992). The climate is only slightly seasonal with a dry period centered on April. Mean annual rainfall is approximately 2700 mm and mean daily temperature is 26.7°C (Danum Valley Field Centre Records, 1986-1993).

Methods

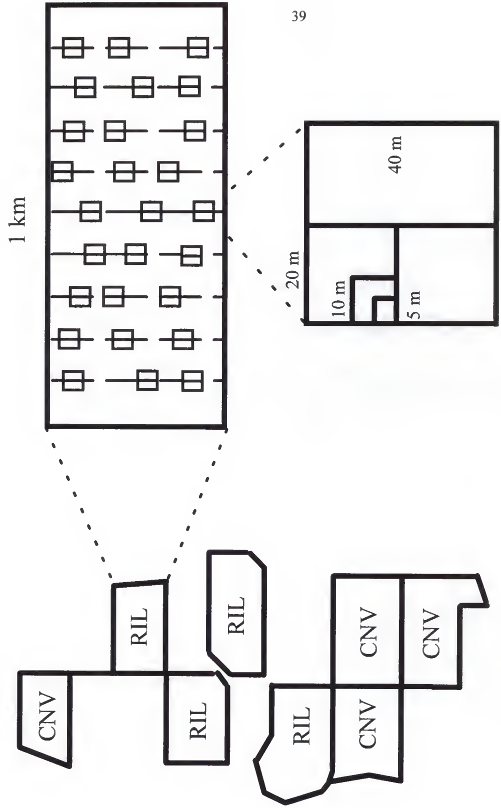
Pre-logging Measurements

Forest biomass and stand structure before logging were measured to allow comparison of the effects of logging treatment on carbon stores. Prior to logging, four logging units (30-50 ha each) were randomly selected from the experimental area to be logged according to the reduced-impact logging guidelines (hereafter RIL units); four additional units were randomly selected from an adjacent area destined to be logged conventionally (Fig. 3-1). Units logged conventionally or by the RIL guidelines were paired according to topography and logging schedule to reduce variability of logging impacts on the residual stand due to differences in soil moisture content and slope. The conventional logging units were harvested by crews not involved in the reduced-impact logging project. A crew that was trained with funds from the power company and was experienced with directional felling and proper log extraction techniques harvested the RIL units according to the reduced-impact logging guidelines.

Experimental Design

Within each unit 20 to 35 1600 m^2 plots (40 x 40 m for 6 units or 20 x 80 m for two units, approximately 10% of each logging unit area) were located according to a stratified random design (Fig. 3-1), avoiding areas within 20 m of permanent streams, within 10 m of a logging unit boundary or a main road, steep rocky areas (slopes >45°), and landslides. In the eight logging units, a total of 216 plots was established. No plots were established at 49 points dismissed due to exclusions listed above.

Figure 3-1. In 8 randomly selected logging units (30-60 ha each; RIL - units logged according to the RIL guidelines, CNV - units logged conventionally), permanent plots (1600 m^2) were established to sample trees and woody vines. Stems were tagged and measured in nested plots as follows: 1600 m^2, trees ≥60 cm dbh; 800 m^2, stems 20-40 cm dbh; 400 m^2, stems 10-20 cm dbh; 100 m^2, stems 5-10 cm dbh; 25 m^2, trees 1-5 cm dbh, and vines 2-5 cm dbh.


1 km
40 m
20 m
10 m
5 m
RIL
RIL
RIL
RIL
CNV
CNV
CNV
CNV

Aboveground Biomass

Each tree >60 cm diameter was tagged and its diameter measured at 1.3 m or above buttresses (hereafter, dbh). Nested subplots were used for smaller trees and lianas (Fig. 3-1). All commercial trees tagged in the plots were identified to species or timber species group. Stem and bark damage were described, and any other tree characteristics that might be mistaken for logging damage were noted. Lianas were tagged and measured only in the four units to be logged conventionally because most of the lianas were cut prior to plot establishment in the units to be logged according to the reduced-impact logging guidelines.

Aboveground tree biomass was estimated allometrically using tree inventory data and stem volume - diameter - height relations calculated for 15 local species groups in the Ulu Segama Forest Reserve (Forestal International Limited 1973; Appendix B) and a Biomass Expansion Factor (BEF) developed for good hill dipterocarp forest in West Malaysia (Brown *et al.* 1989). The BEF for good hill forest was selected over the factor developed for other Malaysian dipterocarp forest types because the basal area for good hill forest (28.5 m^2 ha^{-1} for trees >15 cm dbh) most closely matched that of the study site. Wood densities were available for 120 of the 124 species or species groups recorded in the plots (Burgess 1966). To convert wood densities determined at 12% moisture content (air-dry weight) to density at dry weight, I applied a regression developed by Reyes *et al.* (1992). For non-dipterocarp species whose wood density was not known, I used the arithmetic mean of the known species that were not dipterocarps (0.503 g cm^{-3}, $N = 48$ species). For dipterocarp species whose wood density was not known, I used the mean value of the known species within the genus (or section of the genus, when applicable). Biomass of lianas >2 cm dbh was estimated from basal area using a regression equation developed for Venezuelan liana species (Putz 1983).

To supplement the available stem volume equations, which I judged were inappropriate for trees <10 cm dbh, I harvested 40 randomly selected trees 1-10 cm dbh, representing a mixture of

species and determined their aboveground biomass. Sampling was conducted in primary forest within 1 km of the study sites. A regression equation was calculated with dbh as the independent variable and tree biomass as the dependent variable. To determine total small tree biomass, I applied the dbh-biomass equation to the trees (1-10 cm dbh) in the permanent plots.

Shrub, herb, palm, and herbaceous vine biomass was measured in 3 RIL and 3 conventional logging units using 1 m^2 circular clip plots ($n = 15$ per unit, $N = 45$ per treatment) randomly located in a stratified random fashion using three topographical positions as strata. Each plot was considered a sample and logging unit divisions were assumed to be inconsequential to the estimate as the variation within a unit was much higher than that between units. In the clip plots, all above-ground plant biomass (<1 cm diameter at base) was cut at the soil surface and weighed, and then a subsample was oven-dried at 70 °C to constant mass. For self-supporting species, only plants rooted inside plots were included. For vines, all stems and leaves occurring over the clip plots were collected regardless of the rooting site. Palms (primarily stemless rattans) that occurred in the plots were also clipped and collected.

A conversion factor of 50% is frequently used to estimate carbon content of plant tissues (*e.g.*, Harmon *et al.* 1990; Hoen & Solberg 1994). To determine whether woody tissue in my site was similarly about 50% carbon, I tested a small number of wood samples randomly collected from fresh logging debris for carbon content. Twenty samples, approximately 45 cm^3 each, were collected from log and branch debris. The samples were split into small pieces, oven-dried, ground and sieved. Carbon content was determined using a Carlo-Erba NA 1500 Carbon-Nitrogen Elemental Analyzer (Isotope Ratio Mass Spectrometer, Department of Soil Science, University of Florida, Gainesville, FL). Carbon content averaged 49.2% (SD = 1.1, $N = 20$; statistically different from 50%, $t = 3.55$, df = 19, $P < 0.005$). I assume all plant tissues to be 49.2% carbon by dry weight though I recognize

that certain tissues often have carbon contents that are above or below this percentage (*e.g.*, seeds and fine roots, respectively; Golley 1969; Williams 1986).

Belowground Biomass

Pre-logging root biomass was sampled in the eight logging units using a stratified random design, traversing terrain typical for each unit (n = 10 pits per unit, total N = 40 pits per treatment; logging unit divisions were disregarded in the analyses). Coarse roots (>5 mm diameter) were sampled in 50 x 50 cm monoliths of soil extracted to 50 cm with a sledge-driven flat blade. Roots were separated from the soil in the field and washed, live and dead roots were separated, and sorted into four diameter classes in the lab (5-15, 15-50, 50-150, and >150 mm diameter); and live roots were weighed and subsampled for dry weight determination. Dead roots were weighed and subsampled in a subset of the samples (N = 56). I did not sample deeper than 50 cm in the soil profile for coarse roots and consequently underestimate carbon stored in coarse roots. Fine root (<5 mm diameter) mass was estimated using 5 cm diameter cores taken to 10 cm depth; two cores were taken at each sampling site, combined, soaked in water, and agitated (n = 10 sample sites per unit, total N = 40 per treatment; logging unit divisions were disregarded in analyses). Roots were then separated from soil, oven dried, and weighed. Due to difficulties in confidently differentiating live and dead roots, only total fine root mass values are reported. A few of the early samples were not included as only live roots were dried and weighed.

To determine coarse root biomass directly beneath trees where core sampling was impractical (hereafter, butt roots), 14 partially uprooted trees (20-130 cm dbh) along roadsides and skid trails within the 1993 logging area were opportunistically sampled to establish the relationship between butt root mass and dbh. Coarse roots >10 mm diameter within 1 m of the bole of the tree were separated from the soil, cut into pieces <50 kg, washed, weighed, and subsampled for dry weight determination. Butt root mass was log-transformed and used as a dependent variable in a

regression equation with dbh as the independent variable. To determine total root mass, I applied the dbh - butt root mass equation to trees in the permanent plots and calculated the mean butt root biomass per ha across the eight logging units. Coarse and fine root biomass are expressed on a per ha basis, the calculation of which excluded areas occupied by butt roots.

Damage Assessment and Necromass Production

Permanent plots were recensused for tree damage and survival 5-30 days after logging and again 8-12 months later. All trees and vines were relocated and assessed for damage. Although numerous damage classes were used in the field, here I compress them into the following: destroyed (uprooted and crushed), snapped-off below crown, and other damage (includes crown, stem, bark, or root damage of varying severity).

From the damage assessment data I estimated (by logging unit) the following parameters: timber volume extracted; necromass produced from the branches, leaves, stumps and butt roots of harvested trees; necromass produced from trees destroyed during harvesting; and, necromass produced from damaged trees that died within the first 8-12 months after logging. Aboveground and butt root biomass were included in these calculations.

The biomass of shrubs and herbs in logged forest was measured using 1 m^2 clip plots (n = 15) randomly located along transects dispersed through each of seven logging units (3 RIL, 4 conventional logging) 1 year after logging; the sampling protocol was similar to that used for pre-logging measurements. To determine the biomass of colonizers and resprouted plants in areas with soil disturbance (*e.g.,* skid trails, log landings and roads) 1 year after logging, I sampled skid trails in the same seven logging units using 1 m^2 clip plots (n = 10 per unit, N = 70) located randomly along skid trails. Although skid trails and other areas with soil disturbance covered a relatively small percentage of the total area (conventional logging areas, mean = 11.9%, SD = 2.7, N = 4; RIL areas, mean = 3.5%, SD = 1.6, N = 4; Chapter 2), biomass in these areas was expected to be more variable

than that in the rest of the forest, so sampling intensity was higher. As with pre-logging shrub and herb biomass measurements, logging unit divisions were disregarded in the analyses. Pre- and post-logging measurements of shrub and herb biomass are not paired, as sampling points were located randomly in logging units.

Coarse root mass (both living and dead) was measured 3 months after logging in four logging units (2 RIL, 2 CNV) following the protocol described for the pre-logging measurements. Coarse-root pits were located randomly on skid trails (10 pits per logging unit, $N = 40$) and in other areas of disturbed forest (10 pits per unit, $N = 40$). The difference between mean coarse root biomass before and 3 months after logging (corrected for proportion area in skid trails and disturbed forest) was considered to have entered the necromass pool (if $\text{biomass}_{before} > \text{biomass}_{after}$ at $\alpha = 0.05$). As with understory biomass, logging unit divisions were disregarded thus pre- and post-logging samples were not paired for statistical comparisons. I did not harvest fine roots after logging and assume that fine root mass 1 year after logging is similar to mass before logging.

For all of statistical comparisons I use a significance level of 5% but report test statistics when *P* values are between 0.1 and 0.05. *T*-tests are two-tailed using pooled variances unless stated otherwise. For *t*-tests using separate variances, degrees of freedom were calculated following Brownlee (1965 in Wilkinson 1990). For treatment comparisons based on the aboveground biomass plots, rather than using a global analysis of variance, I use separate t-tests for each diameter class. Nested subplot size was selected for sampling convenience, not to allow equal variances among the diameter classes. The term biomass always refers to living plant material.

Results

Pre-logging Conditions

Stand structure in RIL units was similar to that in conventional logging units prior to logging (Fig. 3-2). The mean number of harvestable trees per hectare (commercial species with dbh ≥60 cm dbh) ranged from 14.4 to 26.9 in the eight logged units (mean = 19.0, SD = 3.88); densities in RIL units did not differ from those in conventional logging units ($t = 0.244$, df = 6, $P > 0.8$). Total basal area of trees ≥10 cm dbh in the eight logging units ranged from 24.9 to 33.1 with an overall mean of 27.5 m^2 ha^{-1} (SD = 2.86). Tree densities for the two treatment areas did not differ for any diameter class (t-tests, $\alpha = 0.05$). In the conventional logging units, density of lianas >2 cm dbh averaged 586 stems per ha (SD = 211, $N = 4$), about 86% of which were <5 cm dbh.

Of the 6298 trees ≥10 cm dbh in the plots, 59.3% (representing 83.3% of the total basal area) were identified to species or species group. Dipterocarpaceae was well-represented in the study area, comprising 29.6% of the tagged trees ≥10 cm dbh and 67.9% of the basal area (Table 3-1). The forest was dominated by two dipterocarp species, *Parashorea tomentella* and *Shorea johorensis*, which together made up 20% of the stems ≥10 cm dbh and 47.8% of the basal area. The 10 most abundant species or species groups were represented similarly in the RIL and conventional logging units. The 15 stem volume equations used in biomass calculations for trees (≥10 cm dbh) along with the species allocated to each are presented in Appendix B.

Total biomass in the two treatment areas averaged about 400 Mg ha^{-1} with approximately 17% occurring below ground (Table 3-2). For each diameter class, aboveground biomass per ha was equivalent for the two treatments (Table 3-2). Approximately 59% of the initial aboveground biomass was in trees ≥60 cm dbh. Small trees (<10 cm dbh) contributed approximately 4% of total aboveground biomass (Table 3-2; Fig. 3-3). Understory plant biomass contributed approximately 1% of total aboveground biomass and was similar in RIL and conventional logging units (Table 3-2).

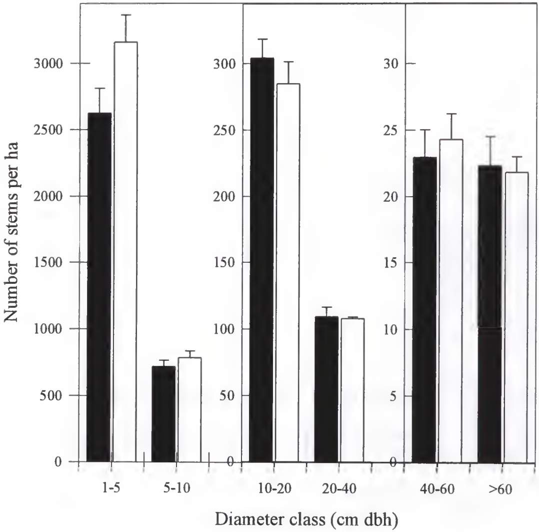


Figure 3-2. Stem density (mean +/- SE) for logging units prior to logging (black bars - units logged according to the RIL guidelines, open bars - units logged conventionally; Note different y-axes). Pre-logging stem densities by diameter class did not differ for the two treatments (*t*-tests with pooled variances, $\alpha = 0.05$).

Table 3-1. The 10 most common species or species groups of trees > 1 cm dbh based on density and basal area (BA, $m^2\ ha^{-1}$) before logging in the eight logging units (all plots, $N = 170$). Merchantable species or species groups are marked with an asterisk.

Species or Species Group	% Stems	Species or Species Group	% BA
*Parashorea tomentella**	12.2	*Parashorea tomentella**	24.1
*Shorea johorensis**	7.8	*Shorea johorensis**	23.8
Eugenia spp.	5.8	Annonaceae	5.4
Lauraceae	5.5	*Shorea parvifolia**	3.5
Diospyros spp.	5.3	*Eugenia* spp.	3.4
Annonaceae	4.0	*Diospyros* spp.	3.4
*Shorea parvifolia**	1.4	*Shorea leprosula**	2.6
*Shorea leprosula**	1.4	*Dryobalanops lanceolata**	2.4
*Dryobalanops lanceolata**	1.4	Lauraceae	2.2
Shorea section *Shorea**	1.1	*Shorea* section *Shorea**	1.7

TABLE 3-2. Above- and below-ground biomass for the two logging treatment areas before logging. Values are means (Mg ha^{-1}), with SD and *N* noted parenthetically. For trees, vines, and butt root mass, SD describes variation among four logging units[a] and does not incorporate error in biomass equations. No significant differences were detected between treatments (*t* tests, $P < 0.05$).

Before Logging	Conventional Logging	Reduced-Impact Logging
Trees >60 cm dbh	190 (35, 4)	190 (53, 4)
Trees 40-60 cm dbh	53 (20, 4)	46 (6.5, 4)
Trees 20-40 cm dbh	46 (2.5, 4)	46 (6.3, 4)
Trees 10-20 cm dbh	21 (2.7, 4)	23 (2.8, 4)
Trees <10 cm dbh	13 (2.0, 4)	12 (2.0, 4)
Vine Biomass	7.6 (3.8, 4)	7.6 (3.8, 4)[b]
Understory Biomass	2.87 (1.50, 45)	2.94 (1.67, 45)
Butt Root Mass	26.8 (6.2, 4)	24.5 (5.7, 4)
Coarse Roots (Alive)[c]	35.9 (33.0, 40)	39.4 (38.7, 40)
Coarse Roots (Dead)[d]	1.6 (2.6, 30)	1.8 (3.5, 26)
Fine Root Mass	2.57 (1.30, 31)	2.74 (1.43, 18)
Total Mean (SD) Biomass Before Logging	399 (40)[e]	394 (59)[e]

[a] Each logging unit considered a replicate and subsampled with 10-27 plots.

[b] Assumed to be equivalent to conventional logging units; no statistical comparison made between treatments.

[c] Log-transformed data used for statistical comparison.

[d] Not included as biomass.

[e] Variance for sum of means calculated using a weighted estimate: $\sum_1^k ((k(w_i)s_i^2)/(n_i))$, where k = # of components, w_i = mean of component/sum of means.

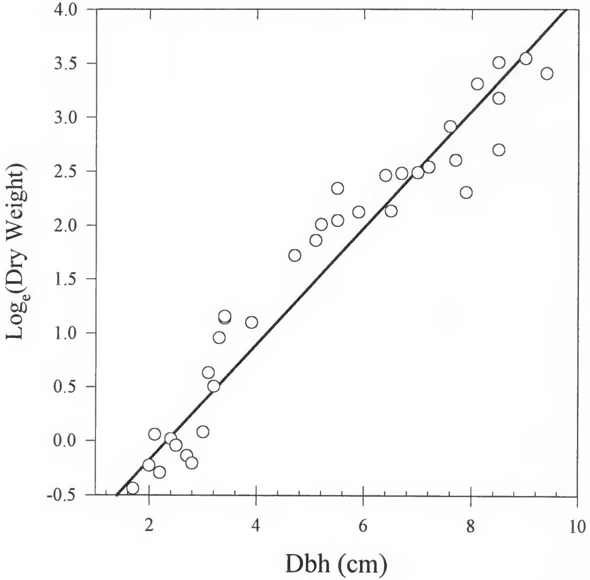


Figure 3-3. Relationship between dbh and total biomass for small trees (1-10 cm dbh), all species combined. The line represents the following regression equation: Log_e (Dry Weight in kg) = 0.539 * DBH - 1.25 ($R^2 = 0.93$, $SE_{slope} = 0.021$, $SE_{intercept} = 0.119$, $P < 0.001$, $N = 40$).

Approximately 2% of the aboveground biomass in conventional logging areas was in vines; small vines (2-5 cm dbh) contributed about 56% of the vine biomass.

Total belowground biomass averaged approximately 66 Mg ha^{-1} in the two treatment areas; about 40% was in butt roots, and about 56% was in coarse roots (Table 3-2). Estimated biomass in butt roots for trees ≥20 cm dbh increased with diameter according to the following relationship: $\mathrm{Log}_{10}(\text{Dry Weight}) = 0.014 * \text{DBH} + 1.51$ (Fig. 3-4). Application of the above regression equation to trees ≥20 cm dbh in the plots used for aboveground biomass yields an overall butt root biomass estimate of 25.6 Mg ha^{-1} (SD = 5.84, $N = 8$). Coarse root biomass (>5 mm diameter) was extremely variable (overall C.V. = 95%; Table 3-2), owing to the presence of widely dispersed, large roots of the canopy trees that may extend more than 35 m away from the tree's stem (see Baillie & Mamit 1983 for discussion). Coarse root mass in the two treatment areas were not different prior to logging (Table 3-2). Mean fine root mass (<5 mm) in the upper 10 cm of soil also did not different in the two treatment areas (Table 3-2).

Details of Logging

Logging started in July 1993 and ended in March 1994 (Table 3-3). The time required to log a unit varied from 1 to 24 weeks. Logging in two of the RIL units was prolonged due principally to wet weather. No dry season occurred during the study period (unpubl. data), and environmental conditions during logging were fairly similar for all units.

A portion of each of the RIL logging units (mean = 44%, SD = 18.9, $N = 4$, range 12 to 63%) was deemed unloggable by the rangers due to steep terrain, unstable substrates, lack of commercial trees, or inaccessibility. Because the principal comparison of this study involves impacts of two harvesting methods, I eliminated these unlogged areas (and any influenced plots) from the analysis. Difficulties arose when trying to identify these areas *a posteriori* but I used the following criterion: if neither a skid trail nor a stump of a harvested tree was inside a plot or within

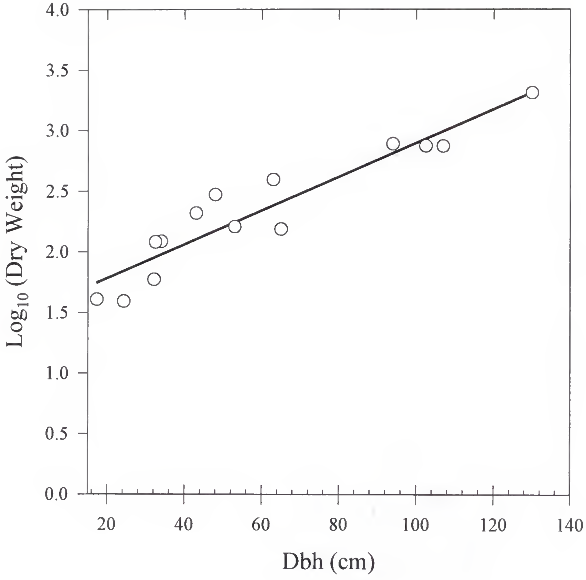


Figure 3-4. Relationship between dbh and butt root biomass for trees >=20 cm dbh. The line represents the following regression equation: Log_{10} (Dry Weight in kg) = 0.014 * DBH + 1.51 ($R^2 = 0.88$, $SE_{slope} = 0.001$, $SE_{intercept} = 0.10$, $P < 0.001$, $N = 14$).

Table 3-3. Dates of logging and volumes of timber removed from reduced-impact logging units (RIL) and conventional logging units (CNV) in Ulu Segama Forest Reserve. Volume extracted is based on data from 1600 m^2 plots distributed among the four units, including total area and only loggable area.

Unit No. -	Dates Logged	Volume Extracted Per Total Area	Volume Extracted Per Loggable Area
32 - RIL	17 Jul '93 - 6 Aug '93	49.7	99.3
41 - CNV	17 Jul '93 - 10 Sep '93	129.6	134.1
36 - RIL	7 Aug '93 - 16 Aug '93	18.5	50.4
38 - CNV	7 Aug '93 - 21 Sep '93	175.9	175.9
30 - RIL	10 Oct '93 - 4 Apr '94	97.6	178.3
23 - CNV	10 Oct '93 - 11 Nov '93	129.9	129.9
35 - RIL	24 Nov '93 - 21 Apr '94	67.7	85.3
39 - CNV	24 Nov '93 - 21 Dec '93	167.8	167.8
		$Mean_{RIL}$ = 58.4	$Mean_{RIL}$ = 103.3
		SD_{RIL} = 33.1	SD_{RIL} = 54.1
		$Mean_{CNV}$ = 150.8	$Mean_{CNV}$ = 151.9
		SD_{CNV} = 24.5	SD_{CNV} = 23.3

30 m of any plot boundary, the plot was considered to be within an unloggable area. By this definition, 48 of the 114 plots in the RIL units were eliminated; none of the 104 plots in the conventional logging units were eliminated.

Mean volume of timber extracted per total unit area ranged from 19 to 176 m^3 ha^{-1} (Table 3-3). If only loggable areas are included in the calculations, mean volume extracted was 152 (SD = 23) in conventional logging and and 103 (SD = 54) in RIL areas. The two treatments did not statistically differ in terms of volume removed from loggable areas (Table 3-3) or associated biomass converted into logging debris (Table 3-4), but small sample sizes and large variances limit the power of this analysis. The Pacific Hardwoods mill that converts the timber extracted from Ulu Segama into lumber, veneer, and blockboard does so with about 50% efficiency (Eng W. H., pers. comm.). Therefore, in addition to the biomass converted to necromass in the forest, I included 50% of the biomass of extracted timber in the necromass pool. (Note: most scrap at the mill is burned to produce electricity; Table 3-4.)

Damage Assessment and Necromass Production

For all dbh classes, proportionally more trees were damaged (all types of damage combined) from logging in conventional logging areas than in RIL areas (one-tailed *t*- tests, arcsine transformed data, $\alpha = 0.05$; Fig. 3-5). Proportion of residual trees damaged differed by dbh class (ANOVA on arcsine transformed data, $F = 3.45$, df = 5,36, $P < 0.02$). Generally, proportionally more small trees were damaged than large trees (Fig. 3-5). There was no interaction in the proportion of trees damaged between logging method and dbh class ($F = 1.4$, df = 5,36, $P = 0.25$).

The percentage of trees destroyed during logging was higher in units logged conventionally than in units logged according to the RIL guidelines for all dbh classes (Fig. 3-5, one-tailed *t*-tests, arcsine transformed data, $\alpha = 0.05$); the mean values by dbh class ranged from 17 to 57% in

Table 3-4. Biomass converted into necromass. Values are means (Mg ha^{-1}), with SD noted parenthetically. SD describes variation among four logging units and does not incorporate error in biomass equations.

	Conventional Logging Units	Reduced-Impact Logging Units
50% of Extracted Timber[a]	32.22 (4.4)	25.50 (11.12)
Branches, Stumps, and Butt Roots of Extracted Trees[b]	67.14 (9.76)	45.93 (22.96)
Destroyed Trees (Uprooted and Crushed)	67.49(45.68)	14.28 (9.56)
Damaged Trees Dead Within One Year After Logging	7.20 (6.90)	4.01 (5.00)
Lianas Destroyed	5.05 (3.23)	6.61 (3.3)
Understory Plant Death[c]	1.74 (1.77)	1.78 (1.94)
Coarse Root Death (Excluding Butt Roots)[c]	10.8 (42.39)	10.4 (48.47)
Total Necromass Produced =	192 (43)[d]	108.5 (22.5)[d]
Mean (SD) Difference Between Two Logging Methods =	86 (43) Mg Necromass ha^{-1}	

[a] 50% of the extracted timber is assumed to be converted into wood products.
[b] Treatment comparison *t*-test with separate variances, $t = 1.79$, df = 3.8, $P = 0.15$.
[c] Represented as the difference between biomass before logging and biomass at 1 yr after logging.
[d] Variance for sum of means calculated using a weighted estimate: $\sum_1^k ((k(w_i)s_i^2)/(n_i))$, where k = # of components, w_i = mean of component/sum of means.

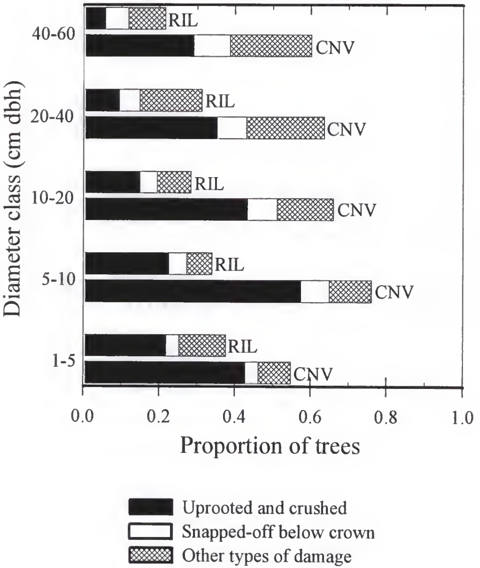


Figure 3-5. Mean proportion of trees completely destroyed, snapped-off, or otherwise damaged (stem, bark, crown, or root) during logging in 4 units of each treatment. The proportion of trees snapped-off or otherwise damaged did not differ for the two treatments (*t*-tests, arcsine transformed data, alpha = 0.05). (Destroyed trees do not include harvested trees.)

conventional logging areas in contrast to 2 to 22% in RIL areas (Fig. 3-5). The biomass in these destroyed trees was assumed to enter the necromass pool (Table 3-4).

The proportion of trees snapped-off (below crown) ranged from 3.5 to 10% across the dbh classes (Fig. 3-5) and was higher in conventional logging than RIL areas for only one of the six diameter classes, trees 10-20 cm dbh (t = 1.77, df = 6, 0.01< P < 0.05; one-tailed t-tests, arcsine transformed data). Snapped-off trees were distinguished from other severely damaged trees because I expected a proportion of these would resprout and would not enter the necromass pool.

The incidence of minor to moderate damage (*e.g.*, crown or bark damage) was higher in conventional logging units than in RIL units for three diameter classes, 40-60 cm dbh (arcsine transformed data, t = 1.97, df = 6, P < 0.05), 10-20 cm dbh (t = 2.17, df = 6, P < 0.05), and 5-10 cm dbh (t = 4.10, df = 6, P < 0.05); the other three diameter classes did not differ (one-tailed t-tests on arcsine transformed data, α = 0.05; Fig. 3-5).

Sixty-seven percent of the vine stems were killed during logging in conventional logging units, contributing an average of 4.68 Mg biomass per ha (SD = 0.18) to the necromass pool. Mortality was evenly distributed across diameter classes (ANOVA, F = 0.49, df = 3,12 P > 0.6). Vines in the RIL units were neither tagged nor measured prior to cutting. To estimate vine biomass killed in the RIL areas I assume that vines cut were killed (87% of stems ≥2 cm dbh cut, F. E. Putz, unpubl. data) and that they represented 87% of the total vine biomass (Tables 3-2, 3-4 & 3-5).

Reassessment

At 8-12 months after logging, many of the damaged trees were dead (Table 3-6). Overall, 18% of the trees (>5 cm dbh) snapped-off below the crown had not resprouted, so were considered dead. In general, trees snapped off at a height >10 m resprouted regardless of logging treatment. The mortality rates for trees receiving other types of damage ranged by dbh class from 0 to 3% in RIL areas and from 3 to 10% in conventional logging areas (Table 3-5). The percentage of these

Table 3-5. Above- and below-ground biomass (and necromass) for the two logging treatment areas 8-12 mo after logging or, in the case of coarse roots, 3 mo after logging. Values are means (Mg ha^{-1}), with SD and N noted parenthetically. For trees, vines, and butt root mass, SD describes variation among logging units and does not incorporate errors in biomass equations. Statistical test results are given for treatment comparisons; pre- and post- harvest comparisons are presented in text.

After Logging	Conventional Logging		Reduced-Impact Logging	Statistical Test Results
Trees >60 cm dbh	49	(15, 4)	100 (16, 4)	$t = 4.12$, df = 6, $P = 0.004$
Trees 40-60 cm dbh	37	(13, 4)	41 (4.9, 4)	$t = 0.58$, df = 3.8, $P = 0.59$[a]
Trees 20-40 cm dbh	29	(5.0, 4)	42 (7.0, 4)	$t = 2.9$, df = 6, $P = 0.03$
Trees 10-20 cm dbh	11	(2.7, 4)	16 (3.6, 4)	$t = 2.22$, df = 6, $P = 0.068$
Trees <10 cm dbh	6.9	(1.2, 4)	9.8 (1.8, 4)	$t = 3.0$, df = 6, $P = 0.02$
Vines	2.6	(1.1, 4)	0.99 (0.49, 4)[b]	no test performed
Understory (Skid Trails)	0.30	(0.38, 40)	0.82 (0.97, 30)	$t = 2.81$, df = 35.6, $P = 0.008$
Understory (Disturbed Forest)	1.24	(1.02, 60)	1.17 (1.03, 45)	$t = 0.33$, df = 103, $P = 0.75$
Butt Roots	11.53	(3.00, 4)	17.39 (2.73, 4)	$t = 2.97$, df = 3.4, $P = 0.05$[a]
Coarse Roots (Skid Trails - Alive)	2.80	(6.08, 20)	1.81 (3.75, 20)	$t = 0.22$, df = 38, $P = 0.83$[c]
Coarse Roots (Skid Trails -Dead)	2.58	(3.32, 20)	8.28 (15.0, 20)	$t = 1.79$, df = 38, $P = 0.08$[c]
Coarse Roots (Disturbed Forest - Alive)	28.1	(30.2, 20)	30.0 (36.8, 20)	$t = 0.38$, df = 38, $P = 0.71$[c]
Coarse Roots (Disturbed Forest - Dead)	0.98	(1.43, 20)	4.08 (14.8, 20)	$t = 0.73$, df = 38, $P = 0.48$
Mean (SD) Total Biomass After Logging[d]	176	(34)[e]	264 (40)[e]	

[a] T-tests performed using separate variances.
[b] Calculated as 13% of pre-logging vine biomass.
[c] Log-transformed data.
[d] Adjusted for area in skid trails RIL = 3.5%, CNV = 12%. Dead coarse roots not included. Fine root mass included assumed equivalent to pre-logging mass.
[e] Variance for sum of means calculated using a weighted estimate: $\sum_1^k ((k(w_i)s_i^2)/(n_i))$, where k = # of components, w_i = mean of component/sum of means.

Table 3-6. Percentage of trees dead at 8-12 mo after logging for each treatment (RIL = reduced-impact logging, CNV = conventional logging). All trees in the four logging units were pooled for each treatment to generate mortality figures; sample sizes *(i.e.,* number of trees) are noted parenthetically. All trees uprooted or uprooted and crushed were assumed dead.

Dbh	Snapped-off		Other Damage		Undamaged	
	CNV	RIL	CNV	RIL	CNV	RIL
≥ 60 cm	14.3% (7)	28.6% (7)	2.7% (37)	0.0% (27)	0.0% (72)	0.0% (101)
40-60 cm	22.0% (18)	42.9% (7)	10.0% (40)	0.0% (15)	0.0% (90)	0.5% (94)
20-40 cm	21.7% (60)	12.1% (33)	8.2% (171)	0.0% (100)	0.9% (352)	0.3% (382)
10-20 cm	17.9% (84)	21.1% (38)	8.2% (171)	2.9% (69)	0.5% (414)	0.0% (509)
5-10 cm	11.3% (53)	10.0% (20)	8.6% (93)	2.9% (34)	1.4% (283)	0.6% (349)
1-5 cm	23.8% (21)	22.7% (22)	6.0% (100)	1.5% (67)	0.5% (374)	0.4% (282)

damaged trees that died during the first year after logging was higher in conventional logging areas than in RIL areas for all diameter classes (Table 3-5). The two logging treatments were not compared statistically because none of the damaged trees in many logging units had died. Although many of the damaged trees were expected to die soon, only the proportions that died before the recensus were incorporated into the necromass pool (Table 3-4).

Between the time the plots were established and the recensus (approximately18 mo after establishment), an average of 0.5% of the undamaged trees (>5 cm dbh) died. The mortality rates for undamaged trees appears similar for the two treatments (Table 3-5).

Shrub and herb biomass 12 months after logging was less than before logging both on skid trails (t- test using separate variances, $t = 12.64$, df = 133.5, $P < 0.001$; Tables 3-2 & 3-5) and in otherwise disturbed forest ($t = 8.97$, df = 193, $P < 0.001$; Tables 3-2 & 3-5). Biomass on skid trails was greater in RIL units than in conventional logging units (Table 3-5). Biomass in other areas of disturbed forest did not differ for the two treatments (Table 3-5). The difference between shrub and herb biomass before logging and at 12 months after logging was considered necromass (Table 3-4).

Three months after logging, coarse root biomass (exclusive of butt roots) on skid trails did not differ between the logging treatments (Table 3-5) but was less than pre-logging levels (log-transformed data, $t = 15.2$, df = 118, $P < 0.001$; Tables 3-2 & 3-5). This decline is probably due to both root death and excavation and relocation from bulldozer activities. Dead coarse root mass on skid trails did not differ between treatments (Table 3-5) and was similar to dead root mass before logging in both conventional (log-transformed data, $t = 1.07$, df = 58, $P = 0.29$; Tables 3-2 & 3-5) and RIL areas (log-transformed data, $t = 1.64$, df = 54, $P = 0.11$; Tables 3-2 & 3-5).

In disturbed forest (not skid trails) 3 months after logging, coarse root biomass did not differ between treatments (Table 3-5) and was similar to pre-logging estimates (log-transformed data, $t =$

1.6, df = 118, $P = 0.11$; Tables 3-2 & 3-5). Dead coarse root mass in logged-over forest did not differ from pre-logging mass (log-transformed data, $t = 1.35$, df = 118, $P > 0.18$; Tables 3-2 & 3-5), nor did treatments differ (Table 3-5). Because conventional logging units had proportionally more area with disturbed soil or skid trails than did RIL units (approx. 12% and 3.5%, respectively; Chapter 2), the calculated total standing stock of coarse root biomass in conventional logging units was less than in RIL units (Table 3-5). My estimates of necromass produced from coarse root death ($biomass_{before}$-$biomass_{after}$) are associated with relatively large standard deviations (Table 3-4), reflecting the large variance in the pre- and post- harvest biomass estimates.

One year after logging, forest areas logged by conventional methods and according to RIL guidelines contained approximately 44% and 67% of their pre-logging biomass, respectively (Tables 3-2 & 3-5). The difference in necromass produced was 76 Mg ha^{-1} (37 Mg C ha^{-1}; Table 3-4). The greater number of residual trees destroyed during logging in conventional logging areas was responsible for approximately 62% of the difference between the two methods; the difference in debris produced from trees felled accounted for approximately 25% of the difference. A large proportion of the standard deviation associated with the estimate of the difference between the two methods is due to variation in coarse root death.

Discussion

Implementation of RIL harvesting guidelines substantially reduced logging damage. The residual forest in the two treatment areas is dramatically different, hence each forest's potential for both short- and long-term carbon storage also differ. In the following sections, I compare my biomass estimates to other dipterocarp forests and briefly discuss estimation methods. I compare levels of logging damage recorded at my sites with other selective cutting operations and discuss ecological implications of reductions in damage for forest recovery. I also discuss the amount of

carbon retained due to implementation of the RIL guidelines, how it could be increased, and how it relates to power plant emissions and other offset options. Finally I identify several issues relevant to future efforts to offset carbon through reduced-impact logging and suggest topics needing further research.

Residual Forest Biomass

Pre-logging aboveground biomass estimates for my sites (291-400 Mg ha^{-1}; mean = 330) are higher than average moist forest biomass in southeast Asia (mean = 225 Mg ha^{-1}, N = 204 stand inventory data sets; Brown *et al.* 1991) but are comparable to estimates for unlogged forests in Sarawak (280-405 Mg ha^{-1}; Brown *et al.* 1991). Big trees (>60 cm dbh) made up about 59% of the pre-logging biomass at my sites. Degraded forests tend to have few big trees and, consequently, have much lower stores of biomass (see Brown *et al.* 1991).

I calculated tree biomass using published regression equations and conversion factors. Both stem volume equations and biomass expansion factors (BEF) are associated with standard errors but these errors were not incorporated into my estimates. I assume that the variance inherent in calculated estimates apply equally to the two treatments. Stem volume equations used in this study were generated from trees within the Ulu Segama area (Forestal International Limited 1973). The BEF, however, was based on data taken from Peninsular Malaysia, Indonesia, Cambodia and Brazil; I did not harvest trees to determine whether or not the selected BEF was appropriate for my site. I also made no provision for hollow trees.

The estimates of necromass produced from logging were based on a relatively large sampling area but did not incorporate the complete necromass pool. No effort was made to measure necromass inputs from trees damaged but not killed (*e.g.,* crowns of snapped off trees, or branches from trees subjected to crown damage) making my estimate conservative. Also, trees snapped-off

below the crown which had resprouted at the 8-12 months census were considered alive, although many of these trees will probably die within the second year post-harvest (Putz & Brokaw 1989).

Data published on belowground biomass in tropical moist forests are sparse and, generally, based on few samples. For example, Edwards and Grubb (1977) excavated roots from 2 pits (10 x 5 m) to a depth of about 25 cm. Sim and Nykvist (1991) excavated roots from 7 pits (0.5 x 0.5 m) to 50 cm depth. My estimate (about 17% of aboveground biomass) falls close to the mean of reported values for tropical moist forests (mean = 19%, range = 7-41%, $N = 7$; Ogawa *et al.* 1965; Hozumi *et al.* 1969; Jenik 1971; Klinge & Rodrigues 1974; Edwards & Grubb 1977; Bullock 1981; Sim & Nykvist 1991). Although I underestimate coarse root biomass by sampling only to 50 cm depth, a more comprehensive root biomass study in dipterocarp forest on similar terrain in Sarawak found most of the lateral coarse roots to be at 15-40 cm below the surface (Baillie & Mamit 1983). For fine roots, my sampling of the upper 10 cm probably included 55-60% of total fine root mass (Green 1993). Bias in my butt root measures are harder to predict. Uprooted trees along roads and skid trails may not have complete root systems and do not represent a random sample from the population; furthermore, I made no effort to separate live and dead sections of root.

Logging damage

In this study, there was no correlation between the proportion of stems fatally damaged and timber volume extracted ($R^2 = 0.39$, $P = 0.37$, $N = 8$; Fig. 3-6). This result is contrary to Nicholson's (1979) finding that logging damage and volume extracted are positively correlated. Across the broad range of volumes extracted in RIL units, fatal damage was less than 20% of the stand, lending support to the conclusion that treatment differences in logging damage were due to logging technique not harvesting intensity.

Relative to other selectively logged tropical forests, the amount of timber removed from my study site was high, as was the level of logging damage. First cuts in Amazonian moist forest

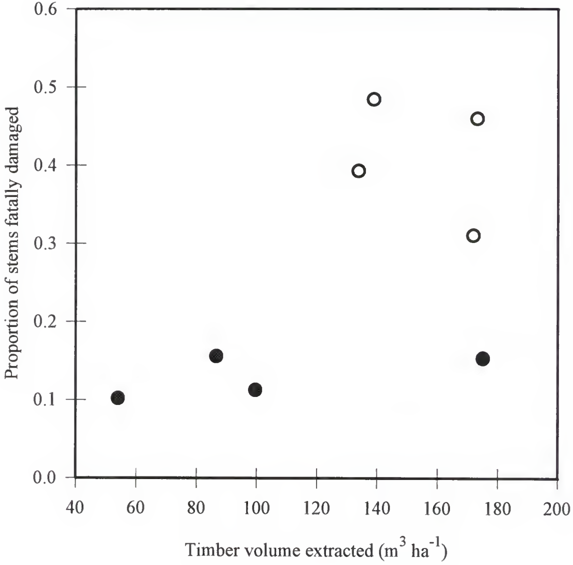


Figure 3-6. Mean proportion of stems (1-60 cm dbh) fatally damaged plotted against mean timber volume extracted (m^3 ha^{-1}; open circles - conventional logging units, solid circles - reduced-impact logging units).

generally take <50 m^3 ha^{-1} (Uhl & Vieira 1989; Thiollay 1992; Verissimo *et al.* 1992); in African forests generally <30 m^3 ha^{-1} of timber is harvested (Nwoboshi 1987; Ola-Adams 1987; Kio & Ekwebelam 1987; Wilkie *et al.* 1992; White 1994). Even though the lack of standard methodologies precludes direct comparisons of results, for four studies where logging damage was reported, damage to residual trees >10 cm dbh averaged 11% (Gabon - White 1994), 18% (Nigeria - Ola-Adams 1987), 26% (Brazil - Uhl & Vieira 1989) and 43% (Brazil - Verissimo *et al.* 1992). The damage recorded in my conventional logging areas (approximately 66%), though higher than the figures from Amazonia and Nigeria, is similar to figures reported for other sites in Sabah (Fox 1968; Chai & Udarbe 1977), Sarawak (Nicholson 1979; Marn & Jonkers 1981), and West Kalimantan, Indonesia (Cannon *et al.* 1994).

Implementation of RIL guidelines in the study area was associated with a reduction in damage to the residual stand, both in extent and severity. In reduced-impact logging areas, ≈27% of trees >10 cm dbh were damaged and ≈19% were dead within the first year after logging, compared with ≈54% damaged and ≈46% dead in conventional logging areas. Efforts to control damage in tropical moist forest in Suriname (Hendrison 1990) and Indonesia (J. G. Bertault & P. Sist pers. comm.) also reduced damage by about half as compared with uncontrolled or conventional logging. The slopes in my sites, on average, exceeded those recommended for ground-based skidding. Switching to an aerial yarding system (*e.g.*, skyline cable yarding), as is generally recommended for slopes >25 degrees (Dykstra 1994), could further reduce damage, as might further training of fellers and bulldozer operators.

RIL areas had about 25% fewer severely damaged residual trees (all dbh classes) than conventional logging areas. Often severe damage (*e.g.*, uprooted, crushed, or snapped-off) is associated with skidding operations and felling trees laden with lianas (Fox 1968; Appanah & Putz 1984). Vine-cutting, planning skid trail locations, and controlling skidding operations may have

been instrumental in reducing severe damage in RIL areas. Reductions in less severe damage (*i.e.*, crown and bark damage) in RIL areas may have been related to directional felling. Directing trees onto skid trails or into gaps created by previously felled trees further reduced overall gap size and felling damage (Hendrison 1990).

<u>Implications for Forest Recovery and Carbon Storage</u>

RIL areas contained nearly 100 Mg more biomass per ha than conventional logging areas 1 year after logging. If both forests were ultimately to recover pre-logging biomass stores, then regardless of conditions immediately following logging, the net difference in stored biomass, at this ending point, would be zero. Given that these are production forests, repeated cutting cycles or conversion to plantations are their probable fates; they are unlikely to be abandoned for the time needed to fully recover biomass. The timescale relevant to this discussion, therefore, may be through the next cutting cycle (generally stated as 60 years but it undoubtedly will be shorter). During this period, differences in growth and mortality rates and other responses to logging could increase or decrease the difference between the two treatments in biomass stores. I expect biomass to continue to decline in both areas for 2-6 years after logging. Following stabilization of mortality rates, I expect biomass accumulation rates to be greater in RIL areas than in conventional logging areas. The rationale behind my predictions is outlined below.

Mortality rates in logged forest are often relatively high for several years after logging relative to pre-harvest levels (Wan Razali 1989). Elevated mortality rates may be due to any or all of the following: a) damage incurred during logging; b) increased exposure and edge effects (*e.g.*, Kapos 1989; Young & Hubbell 1991); c) increased incidence of mechanical damage from vines (Putz 1991) and falling debris (Wan Razali 1989); and d) competition with fast growing trees and vines (Fox & Chai 1982). Conditions in conventional logging areas (*i.e.* proportionally more damaged trees and greater degree of crown exposure) are expected to be associated with higher

mortality rates (Korsgaard 1992). The difference in mortality during the first year of post harvest observations supports this conjecture.

Growth rates in logged forest have been found to be correlated with crown exposure (Korsgaard 1992; Daalen 1993) and, in general, increased growth rates are frequently observed in residual trees following selective logging (Jonkers 1987; Wan Razali 1989), thinning operations (Fox & Chai 1982; Korsgaard 1992), or natural gap formation (Brown & Whitmore 1992). Though fewer in number, the undamaged residual trees in conventional logging areas may show larger growth increments after logging than trees in RIL areas because of the more open canopy conditions after conventional logging. Overall biomass accumulation, however, is expected to be greater in RIL area than in conventional logging areas because of several characteristics of logged dipterocarp forest, discussed below.

First, large canopy openings can lead to extensive vine and pioneer tree invasions (*e.g.,* Chai & Udarbe 1977; Cannon *et al.* 1994). Residual trees infested with vines or overtopped by pioneer trees may experience reduced growth rates (Lowe & Walker 1977; Putz *et al.* 1984). Vine invasions in RIL areas are expected to be less common than in conventional logging areas due to vine cutting before logging and more closed canopy conditions after logging (Appanah & Putz 1984). Pioneer trees may be more likely to colonize conventional logging areas because of more extensive canopy openings and soil disturbance (Chai & Udarbe 1977). Pioneer trees, because of their low wood densities and short life spans, may not accumulate as much biomass per unit area as similar-sized persistent forest species (Jordan & Farnworth 1980). Second, RIL areas contain more undamaged trees and more trees in the larger dbh classes than conventional logging areas, so the residual trees in RIL sites will probably have larger volume increments than residual trees in conventional sites. Third, sites with scraped and compacted soils accumulate biomass more slowly than sites free of heavy soil disturbance (*e.g.,* Maycock & Congdon 1992), and proportionally more soil was severely

damaged in conventional logging areas. For the skid trails that were opened in RIL areas, higher biomass 1 year after logging relative to skid trails in conventional logging areas may reflect less severe soil disturbance due to controlled logging (*e.g.,* restrictions on soil scraping and wet weather logging). The effect of a larger input of nutrients from logging debris in conventional areas as compared with RIL areas is difficult to predict. The input may stimulate tree growth but could lead also to nutrient immobilization by microbes, decreasing nutrient availability for trees (Lodge *et al.* 1994).

To summarize, for some time after logging, I expect carbon stored in both RIL and conventionally logged forests to decline from levels immediately following logging because of high mortality rates and decay of logging debris. If carbon accumulation rates are higher in RIL areas due to low mortality rates and small quantities of decaying logging debris, they will become net sinks for carbon in fewer years after logging than the conventional logging areas.

Carbon Offsets Through Reduced-Impact Logging

In this pilot project I demonstrated that implementation of RIL guidelines in dipterocarp forests that would otherwise be logged in an uncontrolled and destructive manner could result in the short-term retention of, on average, about 42 Mg C ha^{-1} at a cost of approximately U.S.$300 ha^{-1} (J. Tay, pers. comm.). If the carbon "savings" was considered through the next rotation (*e.g.,* 40-60 yr), the difference in carbon stored in RIL areas compared with conventional logging areas is expected to be greater than 42 Mg ha^{-1}. How policy makers will translate this effort into carbon credits is uncertain (Dixon *et al.* 1993; USDOE 1994). Without doubt, however, the time profile of emission reductions or carbon sequestration will be important for determining the consequences of the action for climate change (*e.g.,* Price & Willis 1993).

Forestry-based carbon offset programs, like the Reduced-Impact Logging Project, can supplement but not replace other efforts such as energy conservation, fuel switching, and increased

power plant efficiencies. For example, application of my estimate (43 Mg ha^{-1}) to the loggable portion of the project area (66% of 1400 ha) yields 39,732 Mg C, equivalent to about 11% of the annual emissions from a 200 MW coal-burning energy plant (Freedman *et al.* 1992). Given the ubiquity of poor timber harvesting practices, considerable scope exists for application of reduced-impact logging in other tropical, subtropical, and temperate-zone forests. This approach to offsetting carbon may not be appropriate for forests with large proportions of their ecosystem carbon stored in fallen logs and soil organic matter because harvesting operations can result in large net losses in carbon over time (Harmon *et al.* 1990). A forest's potential for retaining carbon by altering harvesting practices is primarily a function of the forest's biomass, the baseline to which the damage-controlled site is compared, possibilities for damage reduction, and the volume of timber extracted. In the pilot project in Sabah, about 36% (or 15 Mg C ha^{-1}) of the additional carbon retained in RIL areas was related to volume extracted and debris from felled trees (*i.e.* treetops, stumps, butt roots). Reductions in net volume extracted of the magnitude observed in the project in Sabah are not inherent to RIL operations but are related to areas in streamside buffer zones, terrain, expertise of operators, and supervision of field operations. As the project expands in Sabah, I expect differences related to number of trees felled per ha to disappear, as will this proportion of the carbon savings.

As policies supporting forestry-based carbon offset projects develop, so will a system for evaluating potential projects, their credibility, reliability, and verifiability (Dixon *et al.* 1993). Describing the costs and benefits of reduced-impact logging as a harvesting technique is complicated by externalities and undervalued environmental services (Kramer *et al.* 1992). Assessment of the cost-effectiveness of applying RIL techniques for offsetting carbon will require an even more complex analysis. Reduced-impact logging carbon offset programs may be attractive to power companies because, relative to many tree planting programs, the carbon benefits come earlier and

less risk is involved. The risk of losing the investment to pests, fire or disease are small relative to that for trees in industrial plantations with rotations of 7-20 years.

Expansion of the RIL approach to carbon offsetting is predicated on international acceptance of joint implementation. Hesitancy is coming from developing countries suspicious about the motivation of wealthy countries. Also, as nations industrialize they will develop their own need for reducing net emissions. Although it would not be sensible for developing countries to sell all of their inexpensive offset options to the industrialized nations, poorly managed forests abound, and the world's supply of forestry-based carbon offset options is not in jeopardy.

Researchable Issues

Policy makers will look to biologists and foresters to provide estimates of impacts of forestry-based carbon offset programs. Particularly lacking are data on the biomass of very large trees, including roots. For many tropical trees, little is known about the effects of mechanical damage on growth rates, wood quality, fruit production, mortality rates, and pathogen attack. Foresters promote vine cutting as a useful tool for reducing logging damage, but the implications of vine cutting on wildlife species, particularly frugivores and foliovores should be investigated. Logging stimulates leaf production in some species (*e.g.,* Johns 1988) but few data exist describing changes in fruiting phenology or fruit abundance following logging (but see Wong 1983; Johns 1988). The incidence of weed invasions in logged-over forest appear related to gap size, soil disturbance, and pre-logging species composition. Research directed towards elucidation of these relationships could be useful for predicting impacts of harvesting clusters of trees in comparison with scattered individuals and trees growing in areas with climbing bamboo (*Dinochloa* spp.), and the importance of minimizing soil disturbance. Further efforts to quantify the impacts of forest management activities on carbon storage or sequestration rates through models (*e.g.,* Cropper &

Ewel 1987; Dewar 1990; Dewar & Cannell 1992) and the validation of models will contribute to the database from which proposed carbon offset projects can be assessed.

CHAPTER 4

A SIMULATION MODEL OF CARBON DYNAMICS FOLLOWING LOGGING

Reductions in logging damage can result in increased carbon retention in forest biomass (Chapter 3). In this chapter, I examine the effect of this biomass retention on long-term carbon storage over a 60 year period in dipterocarp forest. I present a simulation model of dipterocarp forest development based on FORMIX, a model developed by Bossel & Krieger (1991). My model tracks carbon stored in forest biomass and necromass pools over time and is intended to simulate forest recovery following logging. The amount of carbon stored in a logged or silviculturally managed forest is influenced by factors and processes that are both internal to the system (*e.g.*, species composition, growth rates, decay rates) and external to the system (*e.g.*, rotation times, logging damage, timber volume extracted). The model provides a tool for organizing this information. I evaluate the model using sensitivity analyses and comparisons with field observations and published data on biomass and necromass stores in primary and logged dipterocarp forest. Finally, I use output from simulations to evaluate effects of reductions in logging damage on carbon storage.

Carbon Storage and Patterns of Recovery Following Logging

When timber is removed from a forest, total ecosystem carbon storage declines. Selective cutting often involves harvesting only a few trees, but many others are usually damaged. As damaged trees die and logging debris decomposes, total carbon stored declines further. Only when carbon sequestration in growth and recruitment exceeds carbon losses in death and decay will total

carbon storage increase. Over time and in the absence of large-scale disturbance, ecosystem carbon storage may approach an asymptote, the position of which may or may not be the same as before logging.

Logging may influence a site's potential to store carbon (*i.e.*, height of the asymptote) and the rate at which the forest recovers and sequesters carbon. For example, soil compaction and erosion, often a consequence of ground-based yarding, may decrease site productivity and, consequently, decrease carbon storage potential. If, after selective logging, the residual stand becomes dominated by vines, grasses and sedges, or pioneer trees, growth of persistent forest tree species, many with high wood densities and large stature, may be suppressed for several decades[1]. Changes in forest structure associated with selective logging operations in Sabah influence environmental conditions within the forest and increase the forest's vulnerability to fire (Uhl & Kauffman 1990). An increase in fire frequency also reduces the forest's potential to accumulate carbon in biomass.

The current state-mandated management plan for timber-producing dipterocarp forests in Sabah calls for 60-year cutting cycles. Consequently, logging impacts that influence the rate of carbon storage between logging and 60 years post-logging are of particular interest. The degree to which total carbon stores decline during and after logging depends on many factors, including timber volume extracted and how this volume is distributed among diameter classes, incidental damage to the residual stand, and the degree to which the vegetation responds to opening. Recovery rates will be influenced by site productivity, species composition, changes in necromass stores, long term

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[1] My concept of pioneer tree species includes species that, relative to the common dipterocarp forest species, have low density wood (< 0.4 g cm^3), short lifespans (10-40 years), produce copious quantities of seeds that require relatively high light and temperatures for germination and establishment, and do not maintain an understory seedling bank. I use "persistent" forest species in reference to tree species that are able to establish in shade and that maintain a seedling bank rather than a seed bank.

effects of nonfatal tree damage, the duration of elevated mortality rates following logging, and impacts of soil damage on vegetation recovery.

In this paper I use a computer simulation model of carbon flow in dipterocarp forest following logging to explore the potential influence of several factors on carbon recovery. Specifically, I use output of simulations to address the following questions: 1) Over 60 years, how does mean carbon storage in a logged forest change with reductions in logging damage?; 2) How do changes in post-logging mortality rates affect mean carbon storage and the final biomass storage over 60 years?; and, 3) How might a temporary post-logging shift in species composition affect ecosystem carbon storage patterns over time?

Background and Basic Model Structure

Previous research has clarified some aspects of forest development and the carbon cycle in dipterocarp forest. Primary productivity and organic matter dynamics were studied in a dipterocarp forest ecosystem in the early 1970s, as part of the International Biological Program (IBP) in Malaysia (synthesized in Kira 1978). The researchers presented a pool and flux model of ecosystem carbon cycling for steady-state conditions (Kira 1987). Using a portion of the IBP data, Bossel and Krieger (1991) developed a physiologically driven model of dipterocarp forest development and natural treefall gap dynamics called FORMIX. FORMIX is useful for looking at forest growth and structural development and, in combination with the IBP data, provides a base for modelling carbon flow in dipterocarp forest. As originially published, however, FORMIX does not adequately simulate forest recovery from logging with bulldozers because it does not incorporate community-level and ecosystem changes fundamentally associated with soil disturbance and logging in Sabah. Changes I have identified as potentially important to carbon storage are elevated post-logging

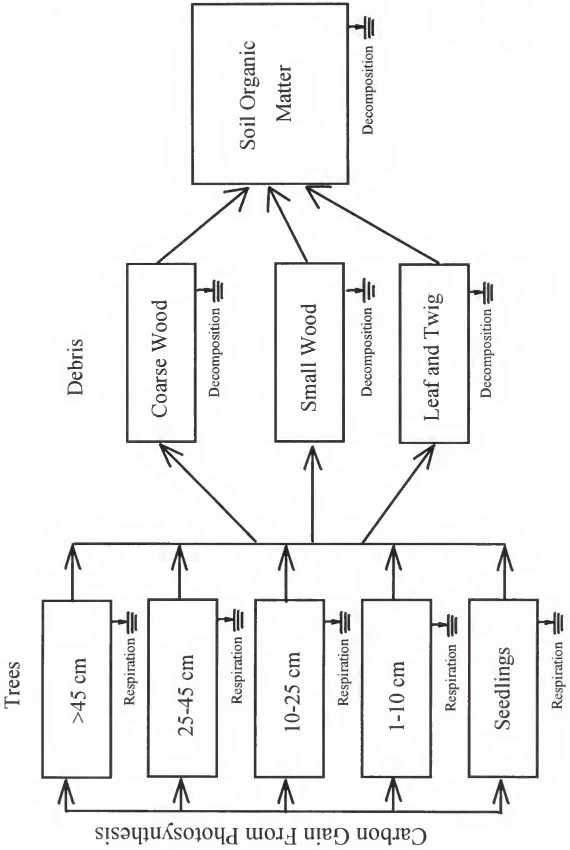
mortality rates, changes in seedling survival, and increased representation of pioneer trees among the recruits.

The model used in this chapter, which I refer to as C-REC (for carbon recovery), tracks carbon stored in dipterocarp forest and is intended to simulate forest dynamics both before and after logging (Appendices C and D). The basic system is scaled to 1 ha, uses annual time steps, and includes carbon pools for aboveground biomass and necromass (Fig. 4-1). Carbon storage in the pools is followed as trees grow, shed litter, die, and are replaced. The basic structure of C-REC is identical to FORMIX, as are processes describing carbon gain through photosynthesis, transition rates between layers, recruitment, and mortality rates. C-REC differs from FORMIX in that it simulates carbon transfer from biomass to necromass through tree mortality and litterfall. Necromass decomposition is simulated as proportional mass loss. Coarse woody, small woody, and fine debris decay include transfer of carbon to soil organic matter. Carbon is lost from the soil organic matter pool at 5% mass loss per year (based on Yoneda *et al.* 1977; Kira 1978). Carbon stored in roots, shrubs, herbs, vines, and in mineral soil below 50 cm is not included in the C-REC model.

Aboveground Biomass

As in FORMIX, I divided the forest into 5 canopy layers (Fig. 4-1) which correspond to the following: Layer 1, canopy trees (>45 cm dbh); Layer 2, subcanopy trees (25-45 cm dbh); Layer 3, pole-sized trees (10-25 cm dbh); Layer 4, saplings (1-10 cm dbh); and, Layer 5, seedlings (0-1 cm dbh). Initial stem densities are entered for a hectare of representative unlogged forest. Input files contain individual trees identified by a number and diameter at breast height (at 1.3 m, hereafter dbh). Initially all trees are assumed to be persistent forest species characterized by attributes of the *Shorea johorensis-Parashorea* group of the Dipterocarpaceae *(e.g.*, photosynthetic rates, allometric

Figure 4-1. Diagram of storages, transfer pathways, and atmospheric exchanges in the C-REC model of carbon flow in a dipterocarp forest.


Trees
>45 cm
Respiration
25-45 cm
Respiration
10-25 cm
Respiration
1-10 cm
Respiration
Seedlings
Respiration
Carbon Gain From Photosynthesis
Debris
Coarse Wood
Decomposition
Small Wood
Decomposition
Leaf and Twig
Decomposition
Soil Organic Matter
Decomposition

relationships, wood density; Table 4-1); Dipterocarpaceae dominate this forest in terms of basal area and tree stem density (Chapter 3). Using these data, stem, branch, leaf, and total biomass are calculated for each tree using diameter-biomass regression equations (Kira 1978; Brown *et al.* 1989). Layers are defined and tracked by total biomass and tree numbers.

Carbon Gain

Annual gross photosynthate production is calculated for each layer and is based on total layer leaf area, incident solar radiation, light attenuation through the canopy, and photosynthetic capacity (following a light response curve; Tables 4-1 and 4-2). Litter production and respiration by fine roots, leaves, and stems are subtracted from gross photoproduction to yield net annual biomass production per layer. A complete description of the basic model is found in Bossel & Krieger (1991).

Transitions

Allometric relationships are used to calculate mean stem diameters and crown projection areas for each layer (Table 4-3). When a layer's mean stem diameter exceeds the maximum diameter set for the layer, a given proportion of the trees (and associated biomass) are transferred to the next layer. Transition probabilities were calculated by Bossel and Krieger (1991). Each layer is associated with two specific mortality rates, a standard rate and a higher rate which applies to crowded conditions. Crowded conditions exist when the layer's canopy is completely closed as determined by crown area/stem diameter ratio, mean stem diameter, and number of trees per layer (Tables 4-1 and 4-3). Recruitment into the seedling layer is controlled by the number of trees >25 cm dbh; each mature tree contributes 1000 seedlings per year (Table 4-1); the base survival rate for established seedlings is 50% per year.

Table 4-1. Characteristics (with code name) of the 2 types of tree species used in the model. Values that differ from those used in FORMIX (Bossel & Krieger 1991) are noted by superscripts. Variables not defined here are defined in Table 4-2.

	Persistent Forest Species	Pioneer Species
P_{max} (g CO_2 m^{-2} hr^{-1})	1.5	2.5[a]
M (g CO_2 hr^{-1} W^{-1})	0.015-0.025	0.04[b]
PR	0.50	0.35[c]
Photosynthetic Production for Litterfall(PSD; proportion)	0.10	0.10
Stemwood fraction (TR)	0.70	0.70
Wood density (G; g cm^{-3})	0.52[d]	0.33[d]
Crown diameter ratio (CD; m m^{-1})	25	32[c]

[a] Bazaaz 1979

[b] Walters & Field 1987

[c] Fox 1968b

[d] Burgess 1966

Table 4-2. Equations describing carbon gain (taken from Bossel & Krieger 1991). Subscripts refer to specific layers that are defined in the text and Figure 4-1.

Solar Radiation Received By a Layer	$I_i = I_{i+1} * EXP(-K_{i+1} * LAI_{i+1})$
Gross Photosynthetic Production	$PS_i = C*(P_{max}/K_i)*LOG_e((1 + (M / P_{max})*I_i)/(1+ (M/P_{max})*I_{i-1}))$
Photosynthetic Production Adjusted for Crown Area	$PT_i = PS_i * AT_i$
Photosynthetic Production Adjusted for Leaf and Root Respiration	$PB_i = PT_i * PR_i$
Photosynthetic Production Adjusted for Stem Respiration	$Cgain_i = PB_i - (R_i * B_i)$

I = radiation above the canopy, 335 W m^{-2}.

K = light extinction coefficient (values per layer in Table 4-3).

LAI = layer leaf area index (maximum values per layer in Table 4-3).

C = conversion factor from g CO_2 m^{-2} hr^{-1} to metric tons of oven dry mass per ha per yr.

M = initial slope of the light response curve (values in Table 4-1).

P_{max} = maximum rate of photosynthesis at light saturation (values in Table 4-1).

AT = current crown fill ratio; represents crown cover per layer.

PR = leaf proportional energy use efficiency; accounts for leaf and fine root respiration.

R = biomass proportional energy loss rate; accounts for stem respiration, 0.06.

B = layer total biomass (Mg oven dry mass ha^{-1}).

Table 4-3. Variables describing the two species groups represented in the C-REC model, by layer. Persistent species refers to tree species able to establish in shade and that maintain a seedling bank rather than a seed bank. Pioneer species refers to tree species that require relatively high light for seedling establishment and that do not maintain a seedling bank.

	Layer 1 >45 cm	Layer 2 25-45 cm	Layer 3 10-25 cm	Layer 4 1-10 cm	Layer 5 Seedlings
Persistent Species					
Mortality Rate (mn_i)[a]	0.005	0.008	0.01	0.05	0.10
Crowding Mortality Rate (mc_i)[a]	0.10	0.15	0.20	0.50	0.50
Post-harvest Mortality Rate (ml)[a]	0.05	0.05	0.05	0.05	0.05
Maximum Leaf Area Index (LAI_i)	2.00	2.00	2.00	2.00	1.00
Transition Rate (TS_i)[a]	n/a	0.02	0.05	0.08	0.10
Pioneer Species					
Mortality Rate (mn_i)[a]	0.01	0.01	0.05	0.05	0.10
Crowding Mortality Rate (mc_i)[a]	0.25	0.25	0.25	0.50	0.50
Post-harvest Mortality Rate (ml)[a]	n/a	n/a	n/a	n/a	n/a
Maximum Leaf Area Index ($LAIP_i$)	2.00	2.00	2.00	2.00	2.00
Transition Rate (TSP_i)[a]	n/a	1.00	1.00	1.00	1.00
Common to Both Groups					
Light Extinction Coefficient (K_i)	0.86	0.86	0.54	0.54	1.00
Form Factor (F_i)	0.38	0.42	0.44	0.45	0.50
Height-Diameter (HD_i; m m^{-1})	40	48	56	67	140
Maximum Diameter (DM_i; m)	n/a	0.45	0.25	0.10	0.01

[a] Expressed as proportions of individuals per hectare.

Necromass

Necromass exists in five compartments: coarse woody debris (branches or logs with diameter >15 cm); small woody litter (diameter ranging from 2 to 15 cm); fine litter (leaves, fruits, twigs <2 cm diameter); and, soil organic matter. Dead roots are not included in the model. Initial pool sizes and decay rates were taken from published data for Malaysian dipterocarp forests (Table 4-4). Annual inputs to the necromass pools include biomass from dying trees and photosynthetic production that goes towards litterfall. Soil organic matter receives annual inputs of coarse woody debris, small woody debris, and fine litter. A proportion of the soil carbon is evolved as CO_2. Soil carbon below 50 cm depth is assumed to be static and is not included in the model; this probably represents about 40 Mg C ha^{-1} (Ohta & Effendi 1992). Root biomass also is not included in the model; this probably represents about 20% of aboveground tree biomass (Chapter 3).

Logging

Impacts of logging on the forest are variable and depend, in part, on timber volume extracted, the harvesting system used, and the extent of damage to the residual stand and to the soil. Selective logging, as currently practiced in Sabah, removes a proportion of trees >60 cm dbh (generally, 8-15 trees per ha), damages a portion of the residual stand, and generates logging debris. The model incorporates the effects of logging in a sequence of steps.

First, timber volume extracted per ha is entered as a variable (m^3). The value is converted into biomass (Mg) using an mean specific gravity (Table 4-2) and is translated into number of trees per ha based on the assumption that stem biomass represents 52.8% of total tree biomass (Biomass Expansion Factor, taken from Brown *et al.* 1989). The biomass and number of trees felled are subtracted from the top layer of the forest (trees >45 cm dbh). Non-stem biomass (*i.e*, branches, leaves, stumps) enters the necromass pools (80% coarse woody debris, 10% small woody debris, 10% fine litter).

Table 4-4. Variables (with code names) describing necromass stores and fluxes, initial conditions listed with reference. O.D.M. refers to oven dry mass.

	Initial Conditions	Reference
Coarse Woody Debris (qc)	49.5 Mg O.D.M. ha^{-1}	Yoneda *et al.* 1977
Woody Litter Conversion to Carbon	50% carbon by mass	Kira 1978
Small Woody Litter (qswl)	2.5 Mg O.D.M. ha^{-1}	This Study
Fine Litter (qfl)	2.4 Mg O.D.M. ha^{-1}	Burghouts *et al.* 1992
Fine Litter Conversion to Carbon	46.9% carbon by mass	Burghouts *et al.* 1992
Soil Organic Matter (qsoil)	33 Mg C ha^{-1}	Ohta & Effendi 1992
Leaf Litter Decay Rate (fldk)	71% mass loss yr^{-1}	Burghouts *et al.* 1992
Leaf Litter to Soil (fltoS)	2.2% transfer to soil yr^{-1}	Burghouts *et al.* 1992
Small Woody Decay Rate (swldk)	50% mass loss yr^{-1}	This Study
Woody Debris Decay Rate (qcdk)	14.4% mass loss yr^{-1}	Yoneda *et al.* 1977
Woody Debris to Soil (qctoS)	4.6% mass loss yr^{-1}	Yoneda *et al.* 1977
CO_2 Evolution From soil (seflx)	5% loss yr^{-1}	Kira 1978

Second, the proportion of trees receiving fatal damage during logging is entered; a single value is used to describe fatal damage for all diameter classes. This proportion of each layer's biomass and individual trees is transferred to the necromass pools (for allocation see Appendix C). This input variable (mean proportion of trees fatally damaged across all layers) is then used to represent the proportion of the 1 ha stand that will be colonized by pioneer tree species rather than by persistent forest species during the first two years after logging.

Prior to logging, pioneer tree species are uncommon in the dipterocarp forests of Sabah (Whitmore 1978; Corner 1988) but they are a dominant component of logged forests in Sabah, often occurring as monodominant stands (Fox 1968b). Pioneer trees are incorporated into the model to provide a way of exploring the impacts of a temporary shift in composition, a shift away from dominance by relatively slow growing, persistent species to relatively fast-growing, colonizing species with low wood densities. Pioneer trees are represented by a suite of physiological and allometric attributes distinct from the trees that dominated the site before logging (*i.e.,* the dipterocarps; Table 4-2).

Bornean species of pioneer trees tend to establish in disturbed sites with open canopy. Establishment patterns suggest that pioneer recruitment increases with some soil disturbance (Putz 1983; Kennedy 1991), but on compacted soils and subsoils typical of skid trails and log landings in Sabah, pioneer tree recruitment is sparse (Pinard *et al.* 1996). In the model, pioneer tree seedlings establish at 13500 seedlings per ha, equivalent to 1.25 Mg O.D.M. ha^{-1} (Pinard *et al.* 1996; Chapter 2).

The model tracks pioneer tree stand development separately from the residual forest. Carbon gain and transitions within the pioneer tree stand subset follow the same processes described earlier for the persisent forest species though specific parameters differ (Table 4-2). Layer transition probabilities for pioneers are set to simulate development of an even-aged (*i.e.,* one layer) stand.

Seedlings of persistent tree species begin to establish under the pioneer tree forest 5 years after logging. Mature residual trees (>25 cm dbh) provide seedlings to the pioneer tree forest. Generally, fruits of dipterocarp trees do not disperse far from parent trees (Ashton 1982) so both the density and distribution of mature residual trees are important for seedling establishment under pioneers. The model assumes that, as the area occupied by pioneer trees increases (*i.e.*, proportion of stand fatally damaged), the proportion of residual trees able to disperse seeds into the pioneer forest decreases. The following equation describes the relationship used in the model to determine the number of individuals contributing seedlings of persistent forest species under the pioneer stand:

$$NST = (N_1 + N_2) * ((1 - DAMF)^2)$$

where NST equals the number of tree contributing seeds in a given year, N_i, the number of trees in a layer$_i$, and DAMF, the proportion of the stand receiving fatal damage.

In Ulu Segama Forest Reserve, observations of planted dipterocarp seedlings suggest that seedlings on skid trails experience higher mortality rates than seedlings off skid trails in logged forest (P. Moura-Costa pers. comm.). The relatively high seedling mortality rates on skid trails are due, in part, to increased incidence of animal browsing and trampling (Pinard, unpubl. data). In the model, survival of seedlings of persistent tree species in the pioneer stand is calculated using the following equation:

$$survPD = basesurvival * (1 - AST)$$

where survPD equals persistent forest species seedling survival in the pioneer stand, basesurvival is the baseline annual seedling survival rate, AST is the proportion of area with soil disturbance. Although seedling growth rates are also affected by adverse soil conditions on skid trails (*e.g.*, compacted soils or nutrient poor subsoils), the model does not incorporate any changes related to carbon gain for trees on skid trails.

Although maximum lifespans of colonizing tree species are variable, the maximum lifespan for the species of *Macaranga* that dominate the pioneers in Ulu Segama, is probably close to 30 years (Fox 1968b). To simulate senescence of pioneers, annual mortality rates of the pioneer trees increase to 50% at 30 years after logging. The model continues to track the "pioneer" stand but, after 35 years, the subset is predominantly trees of persistent species.

During logging, a proportion of the residual stand is damaged but some this damage (*e.g.*, crown or bark damage) does not always cause immediate tree death. This damage is assumed to influence growth rates of affected trees, simulated by removing 25% of the crown area of damaged trees. Growth and yield plot studies in logged dipterocarp forest document an elevation in mortality rates for 2 to 8 years following logging (Wan Razali 1989; Korsgaard 1992). These tree deaths may be related to damage received during logging or may be related to changes in environmental conditions in the residual stand. The model represents this phenomenon by uniform application of 5% mortality rates for five years following logging.

Methods for Simulations and Evaluation

Simulations were run under both no logging and logging scenarios. All carbon pools were tracked over a 60 year period. Longer simulations (1000 yrs) were also performed to evaluate the model's stability. As part of the model evaluation process, a selection of variables, constants and parameters used in the model was increased by 15%, simulations were run, and output values of response variables were recorded. The response variables used in the "sensitivity" analyses for a no-logging scenario were as follows: mean total carbon storage over 20, 40, and 60 years, ending total carbon storage at 20, 40 and 60 years, and ending total biomass in big trees (>45 cm dbh) at 60 years. Because a subset of the variables and parameters was applicable only to a logging scenario, another set of "sensitivity" analyses was conducted assuming 125 m^3 of timber were extracted, 40%

of the residual stand fatally damaged, 20% of the area with soil disturbance, and 20% of the residual stand nonfatally damaged. The response variables used in these logging scenario analyses included those listed above but also included total biomass in pioneer-dominated forest at 20 years.

To evaluate the output of the no-logging scenario, I compared estimates of pre-logging aboveground biomass and necromass stores from the study site with results from simulations run for 60 and 500 years. To evaluate the output of the logging scenario, I compared simulated densities of pioneer trees at 6 and 18 years after logging to data from logged forest in Ulu Segama. Also, simulated estimates of the amount of coarse woody debris 6 years after logging were compared with measurements of detrital stores in logged forest in Ulu Segama.

Model Applications

To evaluate the impacts of timber volume extracted on mean carbon storage, I ran a series of simulations in which damage was held constant and timber volumes were increased from 0 to 200 m^3 in 25 m^3 increments. Mean timber volume extracted from the study sites in Ulu Segama was about 125 m^3 ha^{-1} (Chapter 3), so I used this value for all subsequent simulations.

The rationale for promoting reduced-impact logging as a carbon offset is based on the assumption that more carbon is retained in forest biomass when logging damage is lessened. To evaluate the importance of reduced logging damage for ecosystem carbon storage, I ran a series of simulations holding constant the volume extracted (125 m^3), nonfatal damage (0%), and area in skid trails (20%) but increased the proportion of residual stand killed in 10% intervals from 10 to 90% killed.

In the study sites, about 22% of the individuals in the residual stands in both conventional and RIL areas received damage that did not immediately result in tree death (Chapter 3). To evaluate the potential importance of nonlethal damage to carbon storage, I ran two series of simulations in

which I varied mortality rates following logging. In the first series, the duration of elevated mortality rates (0.01 for all layers) was increased in 1 year increments from 2 to 10 years. In the second series, duration was set at 5 years, and post-logging annual mortality rates ranged from 1 to 12%. To examine the impacts of reducing crown area for the proportion of trees receiving nonfatal damage, I ran simulations reducing crown area of damaged trees from 80% to 10% of full crown. I also ran a series of simulations in which the proportion of nonfatally damaged trees was increased in 10% increments from 0 to 90%, holding volume extracted, area in skid trails, and fatal damage constant.

Conventional and reduced-impact logging, as described by the data in this dissertation (Chapters 2 and 3), differ in terms of volume extracted, fatal damage, and soil damage. To compare the integrated effects of these differences for carbon storage, I ran the model using values observed for each logging method. For conventional logging, the input variables were 154 m^3 ha^{-1} timber extracted, 16.6% area with soil disturbance, 40% of the stand fatally damaged, and 20% of the stand with minor damage. For reduced-impact logging, the input variables were 104 m^3 ha^{-1} timber extracted, 6.8% area with soil disturbance, 20% of the stand fatally damaged, and 20% of the stand with minor damage.

I used mean total carbon storage over time as the response variable for simulations exploring the effects of increasing volume extracted, fatal damage, nonfatal damage, and mortality rates. Results from sensitivity analyses indicated that mean carbon storage was relatively insensitive to small changes in parameter values. For the simulations, I used the following three time intervals: 60 years to represent one cutting cycle, 40 years to represent the NEES-ICSB project lifespan (Chapter 5), and 20 years to allow me to identify trends specific to a shorter time period.

Results and Discussion

Evaluation of Model - Simulations

Over a 1000 year time span, simulated carbon stores in the unlogged forest fluctuate between 200 and 265 Mg ha^{-1} (Fig. 4-2A); mean carbon storage over a 60 year simulation was 220 Mg ha^{-1} (SD = 11). Aboveground biomass ranged from 130 to 220 Mg C ha^{-1} and showed a mean value of 166 Mg C ha^{-1} (SD = 19.5) over a 60 yr simulation, and 170 Mg C ha^{-1} (SD = 23) over a 500 yr simulation. The distribution of biomass across diameter classes fell within the range of values observed in Ulu Segama before logging (Table 4-5). Mean necromass store over a 60 year simulation was 54 Mg C ha^{-1} (SD = 8.9; Fig. 4-2C). Coarse woody debris stores fluctuated between 10 and 60 Mg C ha^{-1} and trends were negatively associated with fluctuations in total biomass stores (Fig. 4-2, B and C). The mean quantity of coarse woody debris over a 60 year simulation (13.5 Mg C ha^{-1}, SD = 7.5) was similar to the mean value recorded in our plots in Ulu Segama (mean = 12.2 Mg C ha^{-1}, SD = 2.3; unpubl. data).

Simulated biomass stores cycled with an approximate 100 year frequency (Fig. 4-2A). Stand dynamics involving fluctuations of the magnitude observed in simulation results could be expected in an area prone to regularly occurring large storms, droughts, or fires but would not be expected if individual treefall gap dynamics were the principal structuring phenomenon in the forest. However, one of the limitations of the C-REC model is that the entire hectare behaves as a unit. When the overstory is "filled" with trees, overstory mortality rates switch to a higher rate, causing a decline in biomass that affects the full hectare, similar to 1 hectare gaps. Natural forest canopy gaps are generally much smaller, $\approx$0.02 ha. A spatially explicit model that incorporates a mosaic of interconnected patches would simulate natural forest dynamics more realistically than the C-REC model, meaning that the extreme fluctuations would be damped (*e.g.*, FORMIX2, Bossel & Krieger 1995).

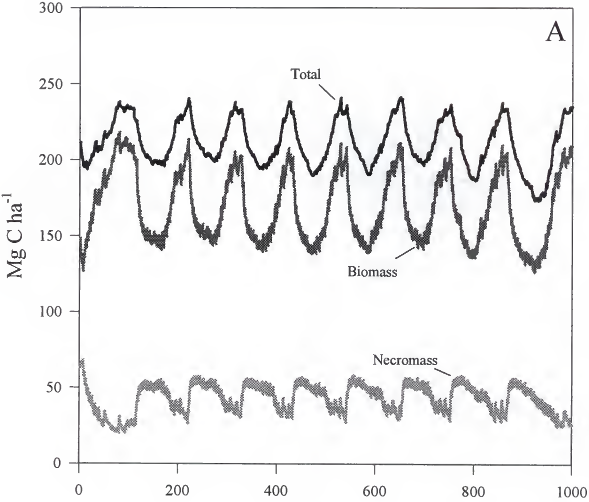


Figure 4-2A. Results from simulation with no logging. Carbon stored in aboveground biomass, necromass, and both (total) over 1000 years.

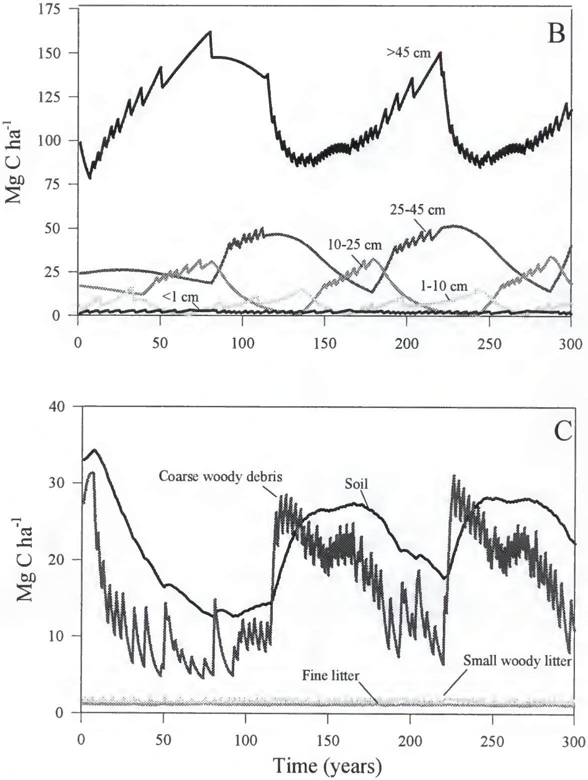


Figure 4-2B and C. Results from simulation with no logging. B) Changes in carbon storage in 5 canopy layers identified by dbh class. C) Changes in carbon storage in soil, coarse woody debris, fine litter, and small woody litter.

Table 4-5. Mean aboveground biomass (Mg C ha^{-1}) for output from model simulations over a 60 year run without logging compared with mean biomass for 8 experimental logging units before logging (Chapter 3).

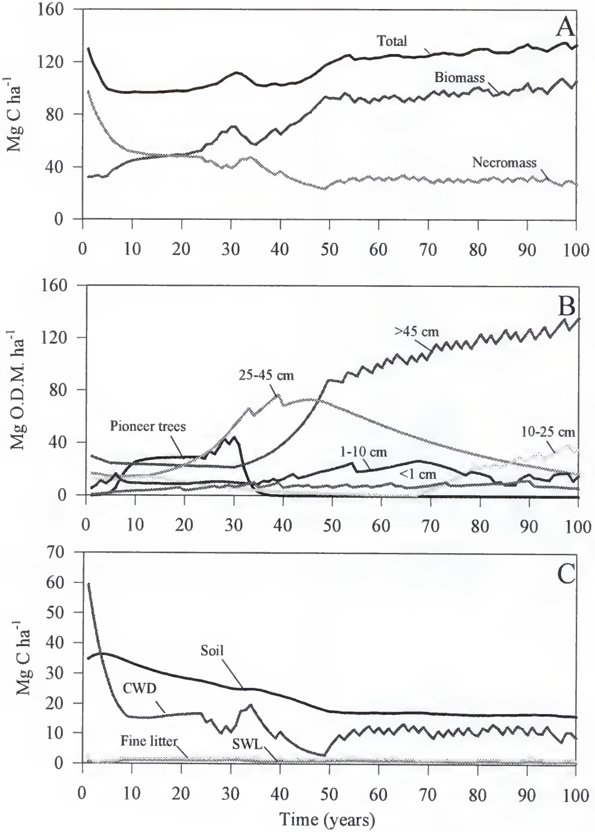
Dbh class	Model Results	Dbh class	Field Measurements
>45 cm dbh	115	>40 cm	120 (28, 8)
25-45 cm	25	20-40 cm	23 (3, 8)
10-25 cm	17	10-20 cm	11 (2, 8)
1-10 cm	8	1-10 cm	7 (1, 8)
<1 cm	3	<1 cm	2 (1, 8)

Following selective logging, carbon storage dropped to a low of 97 Mg C ha^{-1}, 7 years after harvesting (Fig. 4-3A). Ecosystem carbon storage did not reach pre-logging levels (213 Mg C ha^{-1}) within the 500 years after logging (Fig. 4-3A). Carbon storage peaked approximately 120 years after logging (about 150 Mg C ha^{-1}), after which time cycling was similar to that seen in simulations without logging. The mean carbon storage over 60 years after logging was 107 Mg C ha^{-1} (SD = 9.9), about 52% of the level for the no-logging scenario. The small peak in carbon storage that occurred about 30 years after logging was related to a peak in pioneer tree biomass and necromass production associated with the death of the pioneer trees (Fig. 4-3 A, B, and C).

During the first 35 years after logging, only 23% of mean total forest biomass was in pioneer trees even though the pioneer forest dominated 40% of the site (Fig. 4-3B). During the first 60 years after logging, 84% of the mean biomass was in residual trees (Fig. 4-3B). Persistent tree species that establish beneath the pioneer tree canopy increase in importance (for biomass storage) beyond 50 years after logging. Prior to this, these trees represent only 8% of the mean biomass stored per year (7 Mg C ha^{-1}). Before logging, the model forest plot contained 41 trees >45 cm dbh per ha; 60 years after logging, the layer contained 19.3 trees >45 cm dbh per ha.

Results from a simulation of logging (125 m^3, 20% soil disturbance, 40% fatal damage, 20% nonfatal damage), generated pioneer tree densities similar to those observed in logged forest in Ulu Segama Forest Reserve (Chapter 2). At 6 years after logging, simulated pioneer tree density was 1603 stems ha^{-1}, with trees belonging to layer 4 (1-10 cm dbh). At 18 years after logging, simulated density was 51 stems ha^{-1}, at which time all pioneer trees were in the uppermost layer (>45 cm dbh). Observed pioneer tree densities in logged forest, 18 years after logging, overlapped with simulated values (pioneer trees >5 cm dbh, mean = 188, SD = 244) but few pioneers were found with dbh greater than 45 cm.

Figure 4-3. Results from simulations following logging (125 m^3 extracted, 20% soil disturbance, 40% fatal damage, 20% other damage). A) Carbon storage in aboveground biomass, necromass and both (total) across 100 years following logging. B) Carbon storage in canopy layers (by dbh class) and pioneer trees. C) Carbon storage in soil, coarse woody debris (CWD), small woody litter (SWL) and fine litter.


A
Total
Biomass
Necromass
Mg C ha-1
B
>45 cm
25-45 cm
Pioneer trees
10-25 cm
1-10 cm
<1 cm
Mg O.D.M. ha-1
C
Soil
CWD
Fine litter
SWL
Mg C ha-1
Time (years)

Necromass stores reach a low point at 49 years after logging (Fig. 4-3 A, C). The initial decline in coarse woody debris, evident during the first 10 years after logging, reflects carbon losses with the decomposition of logging debris; soil organic matter storage increases only slightly during this time. The rapidly growing pioneer forest contributes a relatively large amount of coarse woody debris between years 10 and 40. For most of this period, conditions in the pioneer forest are crowded, so mortality rates are relatively high. The plateau that is reached in pioneer tree biomass at year 10 (Fig. 4-3B) reflects crowded conditions when the trees are passing through layer 2 (25-45 cm dbh); pioneer tree density is high, carbon gain is relatively high, mean diameter is increasing, and many trees are dying due to competition. Once the threshold diameter (45 cm) is reached (at approx. year 23) the stand again shows an increase in biomass. The decline in coarse woody debris that occurs at about year 23 reflects the low input of debris associated with low tree densities and less mortality. Pioneer tree senescence causes the necromass peak 30 to 40 years after logging. By 60 years after logging, the pattern of carbon storage in coarse woody pool begins to resemble simulation results for the no-logging scenario. Fine litter and small woody litter decline during the first 5 years but by 10 years both pools begin to exhibit fluctuations similar to that observed in results from simulations of the no-logging scenario (Fig. 4-3C).

The results of simulations of logging are similar to direct calculations of logging debris produced (Chapter 3) and field measurements of coarse woody debris in logged forest 6 years after logging. Immediately after conventional logging, the simulated quantity of detritus, coarse and small woody debris, and fine litter was 92 Mg C ha^{-1}. The estimate of aboveground debris produced during logging of the conventional areas, based on stand inventory and logging damage data, was 74.5 Mg C ha^{-1} (Chapter 3). Simulation of RIL logging (described in Chapters 1 and 3) generated 44 Mg C ha^{-1}, 7 Mg C ha^{-1} higher than the measured value.

The simulated value of coarse woody debris stores 6 years after conventional logging was 20 Mg C ha^{-1}, very similar to the observed mean value of 21 Mg C ha^{-1} (SD = 22; unpubl. data). From the field measurements, more coarse woody debris was present in logged forest 6 years after logging than was present in the study site before logging. If we assume that the 6-year-old logged site is a reasonable representation of conventionally logged sites 6 years after logging, the model appears to simulate coarse woody debris dynamics in a reasonable way over this period.

Results from simulations in which timber volumes extracted were varied indicate that, as volume extracted is increased from 0 to 75 m^3, mean carbon storage drops by 20-25% (Fig. 4-4). This decline is principally related to removal of biomass in trees felled. The slopes of the lines for the three time intervals are similar because at these low extraction rates, canopy conditions remain relatively closed and hence, although trees from lower layers grow into upper layers to replace felled trees, total ecosystem carbon storage appears to be similar over 20, 40, and 60 years.

As timber extracted increased from 75 m^3 to 200 m^3, the amount of carbon stored in the forest was strongly affected by the time period considered. Mean carbon storage over 20 years dropped by 16% as timber extracted was increased from 75 m^3 to 200 m^3. For 40 and 60 year intervals, the rate of change in mean carbon storage with increased volume extracted was less (Fig. 4-4). As volume extracted increased from 75 to 200 m^3, mean carbon storage changed only 3-6%. Because logging damage was held at a constant level for these simulations, sufficient numbers of lower canopy trees were available to replace harvested trees, regardless of the number felled and extracted. As more trees were felled, the resulting increase in upper layer canopy openness was associated with positive growth response in trees in lower layers and, consequently, little difference in mean carbon storage resulted. The differences in the relationship between carbon storage and volume extracted for the three time intervals is related to recovery time (*i.e.,* longer time intervals allow more recovery). Results from these simulations suggest that gains in growth compensate for

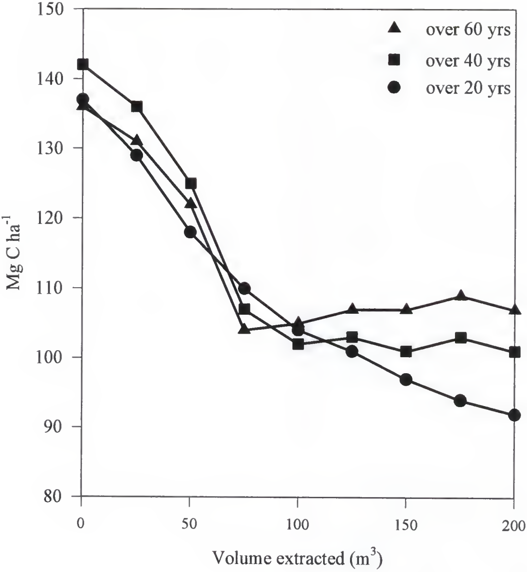


Figure 4-4. Changes in mean carbon storage over 20, 40, and 60 years following logging as volume of timber extracted increases. Logging damage was held constant for all simulations (0% soil damage, 20% fatal damage, 20% other logging damage).

the decrease in standing biomass related to higher levels of timber extraction. The increases in carbon storage over 40 and 60 years as volume extracted increases above 75 m^3 (Fig. 4-4) are an artifact of the assumption that logging damage was constant across the range of extraction levels. In practice, logging damage typically increases as volume of timber extracted increases.

Sensitivity Analyses

Simulation results over 60 years without logging were most sensitive to parameters describing tree allometric relationships and physiological capacities (Table 4-6; Appendix E). In general, biomass in trees >45 cm dbh at 60 years was most sensitive to small changes in input variables, constants, or parameters. For the other response variables examined, no change greater than 15% was observed with an increase of 15% in any one input variable, constant, or parameter.

The model's sensitivity to changes in stemwood fraction and crown area/stem diameter ratio is probably due to the influence of these variables on each layer's leaf area. Leaf area sets the upper limit for carbon gain in photosynthesis and is also used to determine whether conditions are crowded or not, thus setting mortality rates. The allometric statistics used in the model were developed from the destructive harvesting of 150 trees in West Malaysia (Kato *et al.* 1978). The model's reliance on one set of allometric statistics to describe all non-pioneer tree species simplifies forest development processes and does not allow for varying stature, architecture, or wood densities.

The selected response variables were sensitive to small increases in physiological parameters, specifically, the light extinction coefficient for the top layer (K_{45}), stem respiration rate (R), rate of photosynthesis at light saturation (P_{max}), the slope of the light response curve (M), leaf energy use efficiency (PR), conversion factor for photosynthetic gain to organic matter production (C), and LAI_{25}. The model's sensitivity to upper layer's leaf area indices and light attenuation factors suggest that woody biomass accumulation could be affected by invasion of the stand by vines.

Table 4-6. Results from sensitivity analyses. Variables were increased by 15%, and response variables were reported if the value changed by 5% or more. Percent change from base run (unlogged scenario, logging scenario for final three variables) are presented. Complete results from sensitivity analyses are presented in Appendix E. For the response variables, subscripts symbolize the number of years over which the simulation was run, Bio refers to aboveground biomass, C refers to carbon stored in aboveground biomass and necromass (soil organic matter, coarse woody debris, small woody debris, and fine litter), end B45 refers to aboveground biomass in the upper layer (*i.e.*, trees >45 cm dbh) during the final year of the simulation. Numerical subscripts used for input variables refer to canopy layer.

Input Variable	Response Variables							
	mean C_{20}	mean Bio_{20}	end Bio_{20}	mean C_{40}	mean Bio_{40}	mean C_{60}	end $B45_{60}$	$Pioneers_{20}$
B_{25} (initial biomass layer 2)							-31%	
LAI_{45} (leaf are index layer 1)							+5.3%	
LAI_{25} (leaf area index layer 2)							-25%	
TR (stemwood fraction)			-11%		-11%	-5%	+26%	
CD (crown diameter ratio)			-14%		-10%		-39%	
I (full sun illumination)							-30%	
K_{45} (light extinction coefficient)			-9.4%	-5.1%	-5.1%	-6.4%		
P_{max} (maximum photosynthetic rate)				+5.6%			23%	
M (slope of light response curve)							-30%	
C (conversion Ps to organic matter)	+7%	+6.3%		+7.5%		+5.5%	-21%	
PR (leaf energy use efficiency)	+7%	+6.3%		6.1%			-21%	
R (stem respiration)			-11%	-5.6%	-5.8%	-6.4%		
LAI_p (leaf area index pioneers)								+9.6%
P_{maxP} (max. rate for pioneers)								+14%
mc_{45} (crowding mortality rate layer 1)								-14%

The selected response variables were insensitive to small changes in initial amounts of detritus, conversion factors (organic matter to carbon), and mortality rates. The response variables changed little with a 15% increase in initial layer biomass. One exception was biomass in the subcanopy tree layer (25-45 cm dbh); the ending biomass in the canopy layer was 31% less when initial conditions were raised from 48.5 to 56 Mg O.D.M. ha^{-1} (Table 4-6). This increase caused changed little with a 15% increase in initial layer biomass. One exception was biomass in the subcanopy tree layer (25-45 cm dbh); the ending biomass in the canopy layer was 31% less when initial conditions were raised from 48.5 to 56 Mg O.D.M. ha^{-1} (Table 4-6). This increase caused subcanopy tree mortality rates to shift from normal to crowded conditions, so fewer trees made the transition into the canopy layer during the 60 year run. The observed decline in canopy tree biomass at year 60 associated with an increase in LAI_{25} is related to a similar phenomenon of increased growth rates in the subcanopy layer leading to crowded conditions, increased mortality rates, and fewer trees moving into the canopy layer.

For the logging scenario, the response variables changed little with a 15% increase (Appendix E; Table 4-6). Pioneer tree biomass at 20 years was sensitive to a change in maximum leaf area index for the pioneers (LAI_P), maximum photosynthetic rate (P_{maxP}) and crowding mortality rate for pioneers in layer 1 (mc_{45}). Mean carbon storage over 20, 40, and 60 years appeared to be insensitive to small changes in variables, constants and parameters within the model.

Logging Damage and Carbon Storage - Fatal Damage

In general, as fatal stand damage increases, mean carbon storage in aboveground biomass decreases and mean carbon storage in necromass increases (Fig. 4-5, A, B, and C). The relationship between fatal damage and mean carbon storage in biomass is not linear; an inflection point is apparent at about 50 to 60% stand damage for all three time intervals examined. The inflection point marks the level of damage associated with decreased importance of biomass storage and increased

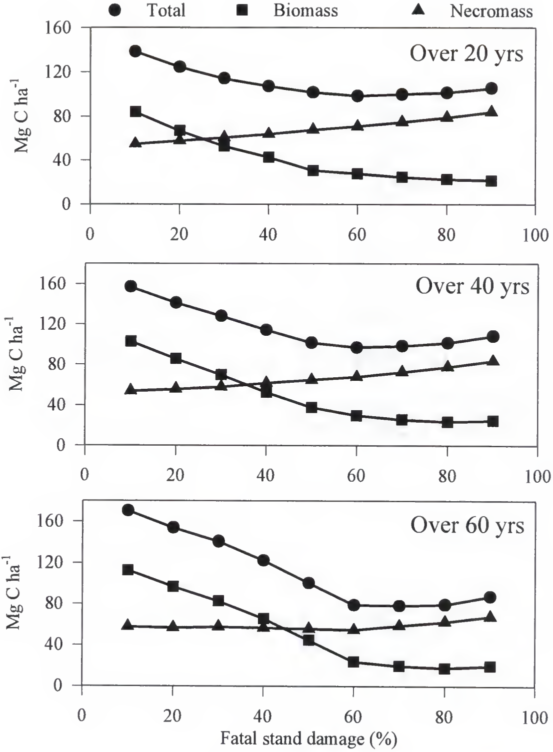


Figure 4-5. Results of simulations in which the proportion of the stand receiving fatal damage was systematically increased in 10% increments. Mean carbon storage in biomass and necromass was calculated over 20, 40, and 60 year periods following logging

importance of necromass storage. If more than 50% of the forest is damaged, standing biomass stores are low, regardless of the time interval considered. When less than 40% of the stand is killed, mean forest biomass increases with longer time intervals.

Necromass produced from trees killed during logging does not disappear immediately. Because of this delay, the three time intervals considered, 20, 40, and 60 years, are associated with slightly different patterns of change in carbon storage as incidence of fatal damage increases. As the time interval considered decreases, the reduction in mean carbon storage associated with an increase in fatal damage is less (Fig. 4-5 A, B, and C).

Logging Damage and Carbon Storage - Nonfatal Damage

Increasing post-logging mortality rates, either the duration of elevated rates or the rate itself, caused a decline in mean carbon storage up to 30% (Fig. 4-6). Increased duration of a relatively high mortality rate (1% yr^{-1}), was associated with an approximately linear decline in mean carbon storage; increasing mortality rate from 1 to 5% caused a 12% decline in mean carbon storage over 60 years. In growth and yield plot studies in dipterocarp forest, on average, mortality rates appear to remain relatively high for about five years (Wan Razali 1989). If mortality rates are high for only one year rather than five years, mean carbon storage over 40 or 60 years is 10% higher. If elevated mortality rates last 10 years rather than five years, the mean carbon storage over a 60 year period drops by 11%.

If nonfatal damage merely reduces individual tree crown areas, results from simulations indicate that mean carbon storage is affected very little. Increasing the proportion of trees with nonfatal damage from 0 to 80% changed mean carbon storage over 20, 40, and 60 years by less than 2%. Increasing the proportion of the crown removed due to nonfatal damage from the 25% to 80% also had little effect on mean carbon or mean biomass storage over time. However, little is known about the effects of wounding on dipterocarp growth and survival. Wounding that does not cause

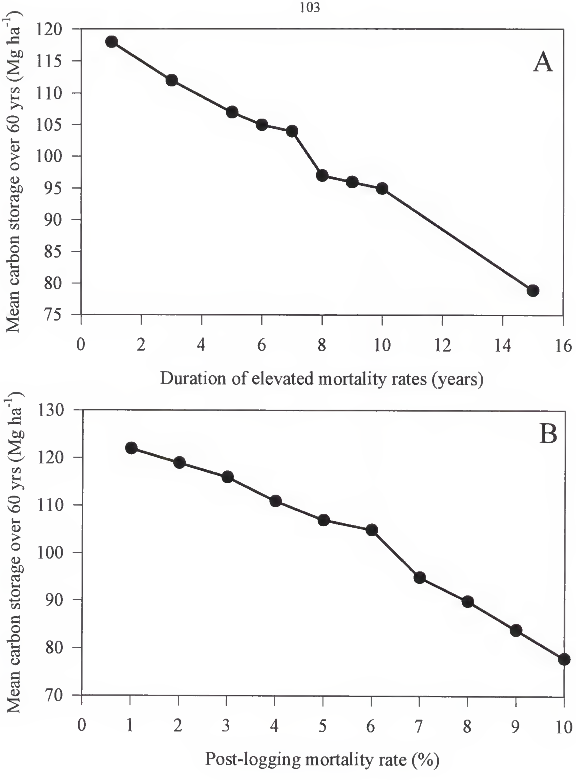


Figure 4-6. Results from simulations in which annual post-logging mortality was systematically increased. Mean carbon storage over a 60 yr period with A) changes in the number of years mortality rates were held at 1%; and, B) changes in the mortality rate for the first five yrs following logging.

death may cause deformities or rots that will reduce the quality of the timber produced (Tay 1993). Certain species of dipterocarps appear to be particularly vulnerable to heart rots (Burgess 1966).

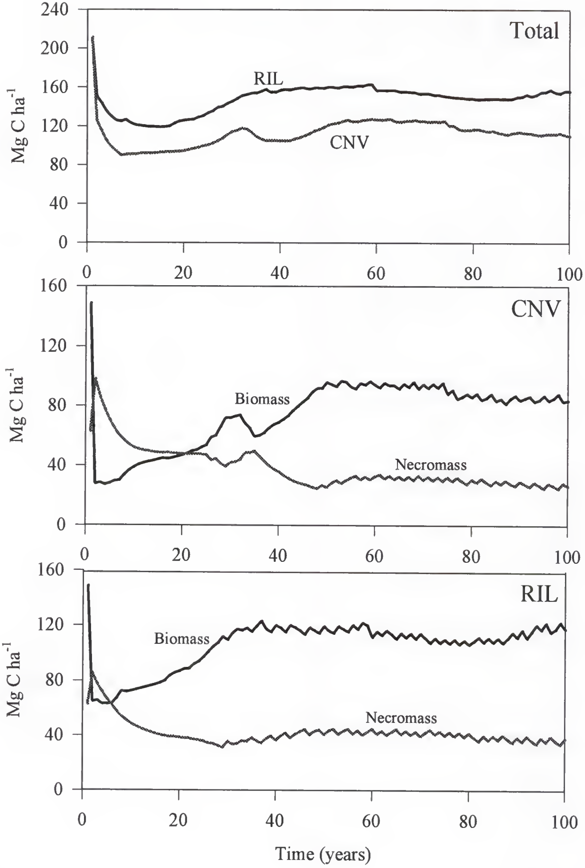
Pioneer Trees

Site occupancy by pioneer trees, as represented in the model, is associated with reductions in total mean biomass over time. Results from simulations suggest that when 20-50% of the stand is killed during logging, as was the case in this study (Chapter 3), replacing persistent forest species with pioneer tree species can reduce the site's potential for carbon storage by 15 to 26% over 40 to 60 years. When the sites are heavily damaged, as when more than 70% of the stand is fatally damaged, pioneer tree invasion is not associated with significant increases in mean biomass storage over 40 or 60 years. In simulations, the establishment of persistent tree species under pioneers is limited by a lack of seedlings when stand damage exceeds 40%. At levels of stand damage less than 40%, the seedlings approaches pre-logging stem densities and biomass within 40 years; the growth of persistent tree species to upper layers is only limited by physiological constraints.

Conventional and Reduced-Impact Logging

Results from simulations indicate that the amount of carbon stored in the forest following reduced-impact logging was between 20 and 40 Mg ha^{-1} higher than that following conventional logging (Fig. 4-7; mean difference over 20 years = 29 Mg C ha^{-1}, mean difference over 60 years = 36 Mg C ha^{-1}). Part of the variation in the magnitude of the difference between the two methods was related to a pulse of carbon storage in pioneer trees following conventional logging. Carbon stored in necromass over time was less in the conventional logging simulation than the RIL simulation. Although the input of logging debris at year 0 was greater following conventional than reduced-impact logging, the coarse woody debris that entered the pool over time was less and decline in soil carbon was greater in conventional than reduced-impact logging (Fig. 4-7). Biomass stabilized at

Figure 4-7. Results from simulations for conventional logging (CNV; 154 m^3 ha^{-1}, 16.6% area with soil disturbance, 40% stand with fatal damage, 20% stand with minor damage) and reduced-impact logging (RIL; 104 m^3 ha^{-1}, 6.8% area with soil disturbance, 20% stand with fatal damage, 20% stand with minor damage). Total carbon includes biomass and necromass. Logging occurred in year 0.


Total
RIL
CNV
Mg C ha-1
240
200
160
120
80
40
0
0
20
40
60
80
100
CNV
Biomass
Necromass
Mg C ha-1
160
120
80
40
0
RIL
Biomass
Necromass
Mg C ha-1
Time (years)

approximately 120 Mg C ha^{-1} after year 30 following reduced-impact logging whereas it stabilized at approximately 85 Mg C ha^{-1} after year 50 following conventional logging. The difference in time to reach stabilization was related to re-establishment of the canopy layer. During the first 40 years following conventional logging, relatively little biomass existed in the canopy layer (Fig. 4-8). Alternately, following reduced-impact logging, the canopy layer recovered to pre-logging biomass levels after about 30 years.

Conclusions

The C-REC model was developed as a tool for examining the effects of reductions in logging damage for ecosystem carbon storage over time. Simulation results indicate that the relationship between fatal stand damage and ecosystem carbon storage is not linear and that at 50-60% fatal stand damage, biomass recovery following logging is severely limited. This threshold damage level is often reached with conventional logging practices in Sabah. Reducing fatal damage from 40 to 20% and area with soil damage from 17% to 7%, as was the case in the Reduced-Impact Logging Project in Sabah (Chapter 3), will be associated with an increase of 36 Mg C ha^{-1} in mean carbon storage over 60 years according to the C-REC model. The difference between the two harvesting methods is due to differences in stand damage than differences in timber volumes extracted.

The C-REC model has several limitations, but perhaps the most important for simulating forest recovery from large-scale disturbances is that only two ecological groups of species are represented. The diversity of tree species that occurs in the dipterocarp forests of Sabah includes a broad range of tree allometries, architectures, canopy heights, reproductive phenologies and physiologies. Simulation results are sensitive to small changes in many of these parameters. If heavy logging damage causes a shift in tree species composition or results in a proliferation of vines, describing the recovering forest with a set of parameters appropriate for the pre-logging composition

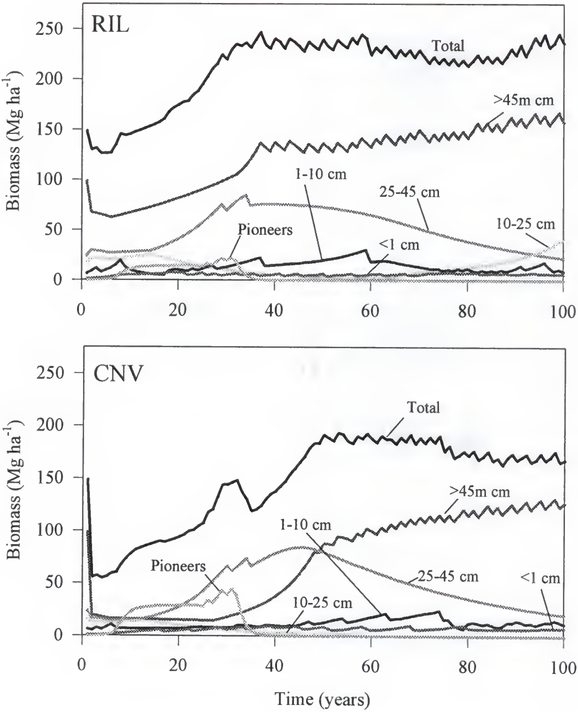


Figure 4-8. Biomass by canopy layer (dbh class) for simulations of reduced-impact (RIL) and conventional (CNV) logging.

may not be satisfactory. A more complex model, however, would be difficult to parameterize due to a lack of data, simulations would be computationally intensive, and evaluation would be more problematic.

In some old growth temperate forests, polycyclic timber harvesting is associated with a substantial decrease in ecosystem carbon storage due to the erosion of necromass stores (Harmon *et al.* 1990). In unlogged dipterocarp forests, only about 25% of ecosystem carbon storage is in necromass (litter and soil), and results from simulations suggest that necromass stores recover to pre-logging levels within a 60 year cutting cycle. Carbon storage in dipterocarp forest is principally in standing biomass. Harvesting activities that influence biomass recovery, for example, by affecting site quality, species composition, and vulnerability to fire, are of consequence to carbon storage. In dipterocarp forests, managing the forest for timber is compatible with maximizing carbon storage if appropriate harvesting practices are used.

CHAPTER 5

REDUCED-IMPACT LOGGING AS A CARBON OFFSET

Introduction

Forestry activities, such as reforestation, forest preservation, enrichment planting, fire protection, reduced-impact logging (Chapter 1; Pinard *et al.* 1995) and other management strategies, provide carbon sequestration services. Following the United Nations Conference on the Environment and Development and the signing of the Framework Convention on Climate Change (FCCC) in 1992, interest in carbon sequestration projects through forestry has grown substantially. National policies and pilot programs are developing in response to a commitment to reduce greenhouse gas emissions to 1990 levels by the year 2000. In this final chapter, I provide an overview of policy developments (to August 1995) in the U.S., criteria for evaluating potential joint implementation (JI)[1], projects, examples of how reduced-impact logging addresses these criteria, and, the cost-effectiveness of reduced-impact logging as a carbon offset.

After ratification of the FCCC in October 1992, the U.S. Department of Energy initiated a voluntary program in which electric utility companies and other polluters within the U.S. would be given guidelines for collecting and reporting information on their greenhouse gas emissions and reductions achieved through any measures (Section 1605 of the Energy Policy Act of 1992, Public

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[1] Joint implementation is a term used to describe cooperative development projects, arranged between two or more countries, that are intended to reduce greenhouse gas emissions or to sequester carbon. Costs of reducing emissions vary among countries, therefore, joint implementation encourages net emissions reductions at a lower global cost than would be possible if every country acted individually.

Law 102-486). Section 1605 included no specific reference to international or overseas efforts (Kinsman & Trexler 1993). A Secretariat for U.S. Implementation of Joint Implementation (USIJI), within DOE, was appointed to develop guidelines for the voluntary program.

The USIJI's guidelines for joint implementation projects recognize some of the commonly cited concerns and criticisms against the JI concept. Several developing countries, principally Malaysia, have been outspoken opponents of joint implementation. Principal criticisms of JI include the following: 1) JI projects, because of their relative cost-effectiveness, might escalate and deter domestic efforts and 2) JI projects may benefit developed countries more than developing countries, may burden developing countries, and may carry unanticipated opportunity costs for host countries (reviewed by Khor 1995). For example, a carbon offset program based on forest preservation would necessarily impose restrictions against incompatible land uses in the project area (*e.g.*, mineral exploration). One goal of the U.S. pilot program is to develop criteria that can be used for evaluating potential JI projects to insure that they support technology transfer, promote sustainable development, improve local capacities, and sequester carbon.

Criteria for Joint Implementation Projects

Criteria upon which joint implementation projects may be evaluated include the following: 1) Does the project include activities above and beyond what would have happened otherwise? 2) Does sufficient information exist to describe what would have happened without the project (*i.e.*, is there a clear baseline)? 3) Have secondary effects, both greenhouse gas and nongreenhouse gas related, been anticipated and identified? Are local capabilities and technologies being developed? 4) Are specific measures being implemented to reduce or sequester greenhouse gas emissions, and have provisions been made for monitoring and verifying greenhouse gas emission reductions or sequestration? 5) Are the participants responsible for greenhouse gas emissions taking measures within their own

country to reduce emissions (USIJI unpubl. document)? In the following sections, I discuss each of these criteria in the context of the RIL pilot project.

Additionality

For a carbon offset project to qualify for JI status, it must involve efforts that are above and beyond what would have happened without the project. This criterion of additionality is intended to insure that new carbon sequestration projects develop and to discourage the repackaging of existing efforts that will continue regardless of new policies that reward carbon sequestration. Additionality is always not easy to demonstrate. For example, in a country where reforestation of degraded lands is mandated, a carbon sequestration program may not increase the number of trees or area planted beyond the goals of the afforestation program. In the case of the Reduced-Impact Logging Project in Sabah, without New England Electric systems's investment, Innoprise Corporation would not have implemented a training program or the RIL harvesting guidelines in the project area. Historical trends in logging practices document few substantial improvements in practices since the 1970s though several foreign assistance projects have presented alternatives to concessionaires and the state forestry department (*e.g.,* Forestal 1973; Malvas 1987).

Baseline

Most carbon offset projects involve a baseline scenario that represents the status quo, or what would have happened if the project did not occur. In some cases, the baseline is concrete and measurable, but, in other cases, the baseline is more abstract and fluid as with fuel switching or forest preservation projects. The baseline used in the RIL project was conventional harvesting practices at the time of logging, specifically the amount of logging damage associated with conventional logging and greenhouse gas emissions related to the death and decay of biomass in damaged trees. In this case, the baseline is described by measurements in conventional logging areas (Chapters 2 and 3). As time passes, the baseline for new projects should shift if logging practices improve in Sabah. If

the infusion of better harvesting practices happens as a result of the New England Electric systems - Innoprise Corporation Sdn. Bhd. RIL project, the associated emissions reductions would be considered positive secondary effects (*i.e.,* leakage).

Secondary Effects

To guard against promotion of projects that have many negative environmental impacts or that lead to increased greenhouse gas emissions elsewhere, potential secondary effects of proposed JI projects need to be identified. In the case of the pilot RIL project in Sabah, environmental impacts included maintenance of more complex forest structure and, associated with this, presumably greater biodiversity and soil conservation. Secondary effects involving greenhouse gas emissions include indirect emissions reductions in other parts of Innoprise's concession where harvesting practices have substantially improved during the lifespan of the project. A possible negative effect concerns timber volumes extracted. Given that the volumes of timber extracted from the RIL areas were less than in conventional logging areas, it is possible that this deficit may have increased the intensity of harvesting elsewhere in the concession. If this were the case, increased greenhouse gas emissions may have been associated with the change in intensity. We cannot fully address this concern, but given that the area to be logged is set a year in advance by the state forestry department, certainly no additional area was harvested due to the project. Wood extracted from the forests in Sabah is used for plywood and sawn timber products, regardless of harvesting method, therefore, no secondary effects were identified related to the fate of the harvested products.

Quantification and Verification of Emissions Reductions

The NEES-ICSB Reduced-Impact Logging Project incorporated measurements of carbon retention and verification of the monitoring program by a third party. In Chapter 2, I described differences in biomass retained in conventional as compared with reduced-impact logging areas and methods used to determine these differences. The RIL Project's monitoring program includes re-

measurements of trees in permanent plots 2 and 5 years after logging. Verification of compliance with the harvesting guidelines and maintenance of the monitoring program is achieved through an environmental audit committee that visits the sites at roughly 6 month intervals (Chapter 1). The audit committee is composed of an appointee of New England Electric systems (a representative from Rainforest Alliance), one appointee of Innoprise Corporation (a representative from the Forest Research Institute of Malaysia), and one joint appointee (a representative from the Departments of Forestry and Botany of the University of Florida).

Other Domestic Actions Being Taken by New England Electric systems

New England Electric plans to reduce their greenhouse gas emissions by 20% or more below 1990 levels (T. Sullivan pers. comm.). Their emissions reduction plan includes tree planting, landfill methane recovery, coal ash recycling, CFC-recycling, fuel-switching, improved forestry programs in their hardwood forest in Massachusetts, and, energy conservation programs. Of the total carbon dioxide emissions reductions included in New England Electric's plan, the Reduced-Impact Logging Project in Sabah represents between 1-12%.

In summary, the Reduced-Impact Logging Project, as implemented in Sabah, meets the criteria for joint implementation projects, proposed by the USIJI Secretariat[2]. Additional criteria will probably develop during the international COP pilot phase, 1995-2000. Cost-effectiveness, for example, will certainly be part of the selection criteria used by industries, such as electric utility companies, considering JI programs.

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[2] In the USIJI's first call for joint implementation project proposals, the New England Electric systems - Innoprise Corporation Sdn. Bhd. Reduced-Impact Logging Project was judged to have met all the criteria for full acceptance into the program but was classified as a "project in development", pending approval by the Malaysian Government (T. Sullivan, pers. comm.).

Valuation of the Carbon Offset Associated with Reduced-Impact Logging

Policies or market forces will, at some point, assign a financial value to emissions reductions or sequestration. Published estimates of the cost of carbon dioxide emissions range from \$2 to \$450 per Mg CO_2 emitted (in Price & Willis 1993). The broad range in estimates is due to differences in assumptions concerning, in part, human and environmental responses to global warming, availability of alternative fuels, and discount rates.

Though the U.S.D.O.E. has not published assumptions appropriate for valuing carbon dioxide emissions, the valuation method ultimately selected will necessarily be strongly linked to time. The reasons for the importance of time in the calculations are twofold. First, the effects of carbon dioxide emissions on climate change involve lag times. For example, with increasing atmospheric CO_2 concentrations, global temperature or sea-level changes will be delayed as ocean temperatures, both surficial and deep water, change (Houghton *et al.* 1990). Second, efforts to reduce emissions or sequester carbon vary temporally. For example, some proposed joint implementation projects involve immediate and permanent reductions in emissions (*e.g.*, fuel-switching, fossil fuels to wind-power) while others involve temporary carbon storage (*e.g.*, pulpwood plantations). In recognition of the temporal variability among projects, discussions of valuing carbon offsets have included concepts such as carbon leasing (Moura-Costa in review) and the relevance of discounting (Price & Willis 1993).

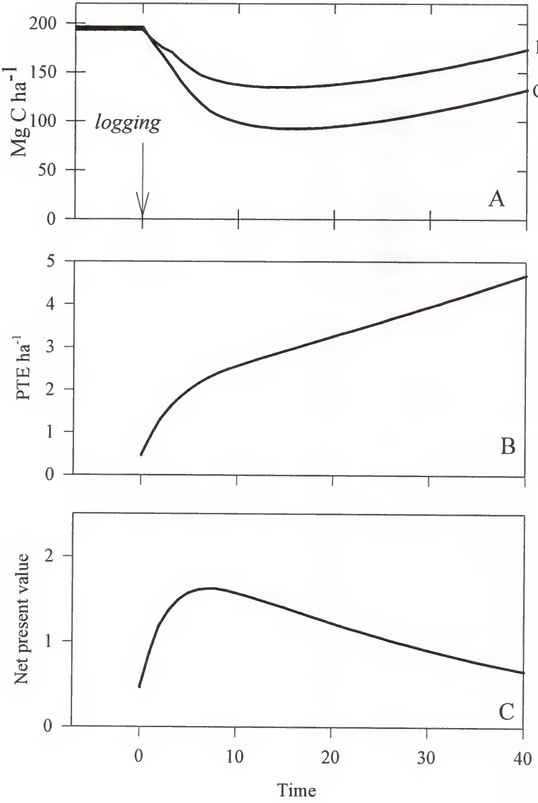
To equate carbon sequestration efforts that vary in time, Richards (1995) developed a method to express temporary carbon storage in units equivalent to permanent carbon storage. The value of the carbon storage can then be described as annual offset payments or credits, with the carbon stored each year expressed as permanent ton equivalents (PTE). The net present value of the project can then be calculated at a given discount rate.

Three steps are involved in Richard's calculation of net present value of a carbon offset. First, annual carbon storage (or emissions reduction) due to the offset effort is described by year of the project (Mg C ha^{-1}) $_{YEAR\ i}$, where i is the year in which a particular amount of carbon is stored per hectare. Second, a linear relationship between atmospheric concentrations of CO_2 and damage to the planet resulting from emissions of CO_2 is assumed. The value or carbon credit for the carbon storage by year is considered equal to 1/20th of a permanent ton equivalent of storage. Third, the series of annual carbon credits is expressed in terms of current equivalents using the following equation: Net present value = $\sum [(1/((1+r)^a))*PTE]$ from $year_0$ to $year_\infty$, where a is the year when the annual storage is achieved and r is the discount rate. Below I present figures describing the net present value of the carbon storage acheived by the RIL project.

The amount of carbon retained due to reduced logging damage can be described as the difference between ecosystem carbon storage in conventional and reduced-impact logging areas (Fig. 5-1A). Projections of the difference between the two logging methods in terms of the rate of carbon storage over time involve many assumptions (e.g., rates of growth, survival, and wood decay; see Chapter 4). Uncertainties surrounding the assumptions become greater as the project lifespan, and thus projection time, increases. Innoprise Corporation guaranteed New England Electric that the 1400 ha project area would not be re-logged within the next 40 years; consequently, the NEES-ICSB RIL project lifespan was set at 40 years. Therefore, the calculations described below assume a 40 year lifespan, and no carbon credits are assigned after 40 years.

Using the area between the curves in Figure 5-1A to represent the carbon stored per year due to RIL and a 5% discount rate, annual carbon credits are calculated as PTE's per ha (Fig. 5-1B). The net present value, expressed as PTEs ha^{-1} over the project lifespan, is 47 Mg C ha^{-1} (Fig. 5-1C). Cost per hectare for the pilot project was about \$344, thus the cost per ton, assuming a 40 year project lifespan, is estimated to be \$7.32 per Mg C ha^{-1}. Cost estimates for carbon offset projects found in

Figure 5-1. A) Schematic diagram of ecosystem carbon storage in dipterocarp forest before and after logging by conventional (CNV) and reduced-impact (RIL) logging. B) Permanent ton equivalents (PTE) per ha over time after logging calculated from annual differences in carbon stored in conventional and reduced-impact logging areas. C) Cumulative permanent ton equivalents discounted over the project 40 yr lifespan.


200
150
100
50
0
Mg C ha-1
logging
RIL
CNV
A
5
4
3
2
1
0
PTE ha-1
B
2
1
0
Net present value
C
0
10
20
30
40
Time

the literature are difficult to compare due to a lack of consistent methodology. Using the above methodology, cost per Mg C for a range of forestry carbon offset projects (*i.e.*, conversion of agricultural lands to forest, enrichment planting, and reduced-impact logging) probably range from \$6 to \$20 per Mg C ha^{-1} (based on data in Richards 1995).

Conclusions

As illustrated by the pilot project in Sabah, reduced-impact logging projects can be designed to meet the general criteria outlined for carbon offsets through joint implementation and may be a cost-effective way to reduce greenhouse gas emissions. The costs of the NEES-ICSB Reduced-Impact Logging Project have been described as \$344 per ha, a figure that represents the costs of stock mapping, pre-planning of skid trails, pre-felling cutting of lianas, and directional felling. Steep slopes and frequent wet-weather shutdowns in the RIL project area resulted in increased harvesting costs. Financial benefits realized in RIL areas included increased skidding efficiency and lower repair and maintenance costs for bulldozers but were not great enough to balance the costs of implementing RIL guidelines (J. Tay, pers. comm.). The environmental benefits of maintaining forest structure and conserving soil are difficult to define in financial terms. If the international community (parties to the Framework Convention) accepts joint implementation programs, and if policy-makers assign a financial value to carbon sequestration services that is above the cost of controlling logging damage (per Mg C stored ha^{-1}), foreign utilities may produce appropriate financial incentives to loggers to improve harvesting practices.

APPENDIX A

REDUCED-IMPACT LOGGING HARVESTING GUIDELINES

Reduced-impact logging planning and harvesting guidelines (condensed from Rakyat Berjaya - Innoprise Corporation, unpublished document, version 4; road specifications not included).

Harvest Plan	Formal plan to be prepared based on stock map (1:5000 scale) showing locations of commercial trees, proposed roads, skid trails, stream crossings, buffer zones, restricted or excluded areas, rocky or otherwise inaccessible areas, and logging unit boundaries. Stream buffer zones to be demarcated on all streams >5 m between banks; buffer zone width varies with stream width. All trees to be felled are to be marked with record number and with a vertical paint blaze to indicate the direction of fall. Potential crop trees of good form and >20 cm dbh to be paint marked with a blue ring if they are at risk of being damaged from felling or skidding.
Vine Cutting	All vines >2 cm dbh to be severed at least 12 mo prior to harvesting; vines in riparian reserves, buffer zones or excluded areas, and figs are not to be cut.
Skid Trail Planning	Skid trails to be located on ridges and designed to minimize skidding distances, skidding on steep slopes, skidding downhill, and stream crossings. Skid trails to be marked in field prior to harvesting and their endings clearly marked. Side cutting is permitted only on slopes >20°. Construction of skid trails that can not easily be drained is to be avoided.

Tree Felling	Decisions on felling directions to be based on safety to feller, ease of skidding, and avoidance of damage to harvested tree and potential crop trees . Trees to be felled within 10° of indicated direction. Fellers to be trained in use of wedges and equipped with them.
Skidding	Use of the bulldozer's blade is permitted only during skid trail construction on slopes >15°. Skid trail gradients not to exceed 20° except over short distances. Skidding should not occur on slopes >35°.
Landings	Where possible all log landing operations to be carried out on existing roads. Where required, landings to be located on ridges and are not to exceed 0.18 ha.
Closing Operations	Roads and skid trails to be drained, temporary stream crossing structures to be removed, and landings should be reshaped to assure adequate drainage. Available logging debris from perimeter to be redistributed on landing surface.

APPENDIX B

STEM VOLUME EQUATIONS AND WOOD DENSITIES

Biomass calculations in Chapter 3 were based on stem volume equations (Forestal International Limited 1973) and biomass expansion factors (Brown *et al.* 1989). I used stem volume equations developed from destructive sampling of trees within the Lahad Datu district (Ulu Segama Forest Reserve). Measurements made on felled trees were specifically to determine the total gross wood volume between a stump height of 0.6 m (or at top of buttresses) to a top height at the crown point. Diameter over bark and bark thickness were measured at 0.6, 0.7, 2.45, and at successive 2.45 m intervals until the crown point was reached (4.88, 7.33, 9.78, 12.22, 14.68, 17.13, 19.58, 22.03, 24.48, 26.93, . . .). Bole length from stump to 3 diameters (45.7 cm, 30.5, and 10.2 cm) and to crown point was measured. Detailed descriptions of sampling protocols can be found in Forestal International Limited (1973).

Height - diameter equations were prepared using the general equation form of $H = a + bD + cD^2$ where H is height and D is dbh. Volume of each measured tree was calculated using Smalian's formula. A form factor (actual volume of tree bole/volume of a cylinder of same length and basal diameter) was derived for each tree measured and species which had similar form factors were grouped. Volume equations were derived for each of the 15 species groups using the general form of $V = a + b\,(D^2H/100) + c\,((D^2H)/100)^2$ where V is volume (Table B-1). Wood densities were taken from Burgess (1966; Table B-2).

Table B-1. Height and stem volume equations used in Chapter 3 (taken from Forestal International Limited 1973). H = height (m), D = diameter at breast height (cm), N = number of trees sampled, V = stem volume (m^3).

No.	Height	N	R^2	Stem volume	N	R^2
1	$H = 5.506+0.4119*D-0.00162*(D^2)$	151	0.84	$V = 0.038+0.0053*((D^2)*H)/100$	91	0.99
2	$H = 2.614+0.5529*D-0.00302*(D^2)$	262	0.85	$V = 0.1532+0.005*((D^2)*H)/100$	172	0.99
3	$H = -0.3622+0.6403*D-0.00337*(D^2)$	275	0.88	$V = -0.0362+0.005*((D^2)*H)/100+0.00000005*(((D^2)*H)/100)^2$	98	0.99
4	$H = -0.3152+0.7511*D-0.00429*(D^2)$	145	0.88	$V = -0.0364+0.005*((D^2)*H)/100$	94	0.99
5	$H = 2.517+0.5997*D-0.00322*(D^2)$	136	0.85	$V = 0.164+0.0041*((D^2)*H)/100+0.00000041*(((D^2)*H)/100)^2$	96	0.99
6	$H = 5.0849+0.33498*D-0.00102*(D^2)$	162	0.86	$V = 0.1363+0.0046*((D^2)*H)/100+0.00000007*(((D^2)*H)/100)^2$	83	0.99
7	$H = 3.999+0.425*D-0.00195*(D^2)$	200	0.79	$V = 0.1292+0.0047*((D^2)*H)/100+0.00000015*(((D^2)*H)/100)^2$	90	0.99
8	$H = 2.528 +0.3635*D-0.0019*(D^2)$	666	0.75	$V = 0.0582*0.0048*((D^2)*H)/100$	142	0.99
9	$H = 2.297 + 0.3304*D-0.00144*(D^2)$	638	0.76	$V = -0.0145+0.0056*((D^2)*H)/100$	131	0.99
10	$H = 3.981+0.2848*D-0.00119*(D^2)$	509	0.71	$V = 0.0322+0.0054*(D^2)*H)/100$	49	0.99
11	$H = 2.056+0.4659*D-0.00221*(D^2)$	141	0.89	$V = -0.0195+0.0047*((D^2)*H)/100$	47	0.99
12	$H = 11.46+0.263*D-0.00114*(D^2)$	50	0.72	$V = -0.1918+0.0058*((D^2)*H)/100$	23	0.99
13	$H = 3.497+0.238*D-0.00152*(D^2)$	189	0.62	$V = 0.0547+0.0053*((D^2)*H)/100$	49	0.99
14	$H = -3.189+0.7358*D-0.00472*(D^2)$	316	0.88	$V = 0.02997+0.0039*(D^2)*H)/100+0.00000018*(((D^2)*H)/100)^2$	48	0.99
15	$H = 3.329+0.2638*D-0.00136*(D^2)$	343	0.68	$V = -0.0021+0.0051*((D^2)*H)/100$	79	0.99

Table B-2. Species or species group allocations to volume equations (based on Chai *et al.* unpubl doc) and wood densities (g cm^3) used for calculations in Chapter 3 (based on Burgess 1966).

Taxa	Family	Volume equation	Wood density
Agathis dammara	Araucariaceae	14	0.4034
Alstonia spp.	Apocynaceae	8	0.5774
Anacardiaceae	Anacardiaceae	8	0.5234
Anisoptera costata	Dipterocarpaceae	2	0.4874
Anisoptera spp.	Dipterocarpaceae	2	0.4934
Annonaceae	Annonaceae	8	0.3734
Anthoshorea group	Dipterocarpaceae	2	0.3914
Aquilaria malaccensis	Thymelaeaceae	15	0.2894
Artocarpus spp.	Moraceae	15	0.3734
Burseraceae	Burseraceae	10	0.5534
Calophyllum sp.	Clusiaceae	8	0.4934
Campnosperma auriculata	Anacardiaceae	15	0.3374
Castanopsis	Fagaceae	9	0.5294
Cratoxylum arborescens	Hypericaceae	9	0.6854
Dactylocladus stenostachys	Melastomataceae	15	0.3736
Dialium spp.	Leguminosae	9	0.7334
Dillenia spp.	Dilleniaceae	15	0.5534
Diospyros spp.	Ebenaceae	8	0.5534
Dipterocarpus spp.	Dipterocarpaceae	5	0.6134
Dipterocarpus acutangulus	Dipterocarpaceae	5	0.5894
Dipterocarpus caudiferus	Dipterocarpaceae	5	0.5150
Dipterocarpus confertus	Dipterocarpaceae	5	0.6146
Dipterocarpus crinitus	Dipterocarpaceae	5	0.6974
Dipterocarpus geniculatus	Dipterocarpaceae	5	0.5822
Dipterocarpus gracilis	Dipterocarpaceae	5	0.5798
Dipterocarpus grandiflorus	Dipterocarpaceae	5	0.6062
Dipterocarpus humeratus	Dipterocarpaceae	5	0.5870
Dipterocarpus lowii	Dipterocarpacreae	5	0.6494
Dipterocarpus pachyphyllus	Dipterocarpaceae	5	0.5810
Dipterocarpus warburgii	Dipterocarpaceae	5	0.5066
Dipterocarups ochraceus	Dipterocarpacreae	5	0.5882
Dracontomelon puberulum	Anacardiaceae	15	0.4634
Dryobalanops beccarii	Dipterocarpacreae	4	0.5618
Dryobalanops keithii	Dipterocarpaceae	4	0.5378
Dryobalanops lanceolata	Dipterocarpacreae	4	0.5654
Dryobalanops spp.	Dipterocarpaceae	4	0.5654

Taxa	Family	Volume equation	Wood density
Duabanga moluccana	Sonneratiaceae	15	0.3134
Durio sp.	Bombacaceae	8	0.4934
Dyera spp.	Apocynaceae	8	0.3614
Endospermum peltatum	Euphorbiaceae	15	0.3734
Eugenia spp.	Myrtaceae	9	0.6254
Eusideroxylon malagangai	Lauraceae	13 (to 15)	0.5270
Eusideroxylon zwageri	Lauraceae	13	0.8820
Fagraea fragrans	Loganiaceae	15	0.6194
Heritiera simplicifolia	Sterculiaceae	15	0.5774
Hopea beccariana	Dipterocarpaceae	2	0.6038
Hopea sangal	Dipterocarpaceae	4	0.5414
Hopea spp.	Dipterocarpaceae	2	0.5534
Intsia palembanica	Leguminosae	9	0.6494
Koompassia excelsa	Leguminosae	12	0.6374
Koompassia malaccensis	Fabaceae	12	0.6734
Koordersiodendron pinnatum	Anacardiaceae	8	0.6134
Lauraceae	Lauraceae	9	0.4934
Lithocarpus & Quercus	Fagaceae	9	0.6518
Lophopetalum spp.	Celastraceae	15	0.4334
Lumnitzera sp.	Combretaceae	15	0.5894
Mangifera spp.	Anacardiaceae	9	0.4634
Meliaceae	Meliaceae	8	0.4634
Myristicaceae	Myristicaceae	15	0.4934
Neolamarkia cadamba	Rubiaceae	14	0.3254
Octomeles sumatrana	Datiscaceae	15	0.2774
Parashorea malaanonan	Dipterocarpaceae	3	0.3974
Parashorea parvifolia	Dipterocarpaceae	3	0.3974
Parashorea spp.	Dipterocarpaceae	3	0.3974
Parashorea tomentella	Dipterocarpaceae	3	0.3974
Pentace spp.	Tiliaceae	9	0.5654
Planchonia valida	Lecythidaceae	8	0.6074
Podocarpus	Podocarpaceae	14	0.4454
Pterospermum sp.	Sterculiaceae	15	0.5174
Richetia section Shorea	Dipterocarpaceae	6	0.4334
Rubroshorea section Shorea	Dipterocarpaceae	2	0.3734
Sapotaceae	Sapotaceae	9	0.5114
Scaphium affine	Sterculiaceae	9	0.4334
Scorodocarpus borneensis	Olacaceae	8	0.6854

Taxa	Family	Volume equation	Wood density
Shorea acuminatissima	Dipterocarpaceae	6	0.4190
Shorea agami	Dipterocarpaceae	2	0.5126
Shorea almon	Dipterocarpaceae	2	0.4070
Shorea andulensis	Dipterocarpaceae	2	?
Shorea argentifolia	Dipterocarpaceae	2	0.6350
Shorea atrinervosa	Dipterocarpaceae	7	0.7334
Shorea beccariana	Dipterocarpaceae	2	0.4382
Shorea bracteolata	Dipterocarpaceae	2	0.3914
Shorea cristata	Dipterocarpaceae	2	0.6338
Shorea dasyphylla	Dipterocarpaceae	2	0.3734
Shorea exelliptica	Dipterocarpaceae	7	0.7154
Shorea faguetiana	Dipterocarpaceae	6	0.4742
Shorea gibbosa	Dipterocarpaceae	6	0.4178
Shorea glaucescens	Dipterocarpaceae	?	0.6422
Shorea guiso	Dipterocarpaceae	7	0.8054
Shorea hopeifolia	Dipterocarpaceae	6	0.4490
Shorea hypoleuca	Dipterocarpaceae	7	0.7166
Shorea johorensis	Dipterocarpaceae	1	0.4046
Shorea kudatensis	Dipterocarpaceae	6	0.4922
Shorea laevis	Dipterocarpaceae	7	0.7454
Shorea leprosula	Dipterocarpaceae	2	0.3782
Shorea macroptera	Dipterocarpaceae	2	0.3914
Shorea maxwelliana	Dipterocarpaceae	7	0.7946
Shorea mecistopteryx	Dipterocarpaceae	2	0.4250
Shorea multiflora	Dipterocarpaceae	6	0.5066
Shorea obscura	Dipterocarpaceae	7	0.7994
Shorea oleosa	Dipterocarpaceae	2	0.3794
Shorea ovalis	Dipterocarpaceae	2	0.3950
Shorea ovata	Dipterocarpaceae	2	.03950
Shorea parvifolia	Dipterocarpaceae	2	0.5174
Shorea pauciflora	Dipterocarpaceae	2	0.5114
Shorea platycarpa	Dipterocarpaceae	2	0.5654
Shorea playclados	Dipterocarpaceae	2	0.5654
Shorea scabrida	Dipterocarpaceae	2	0.4142
Shorea section Shorea	Dipterocarpaceae	7	0.8054
Shorea seminis	Dipterocarpaceae	7	0.7298
Shorea smithiana	Dipterocarpaceae	2	0.3866
Shorea spp.	Dipterocarpaceae	2	0.5130

Table B-2 (continued).

Taxa	Family	Volume equation	Wood density
Shorea superba	Dipterocarpaceae	7	0.6602
Shorea symingtonii	Dipterocarpaceae	2	0.4034
Shorea venulosa	Dipterocarpaceae	2	0.6158
Shorea waltonii	Dipterocarpaceae	2	0.3470
Shorea xanthophylla	Dipterocarpaceae	6	0.5066
Sindora spp.	Leguminosae	9	0.5234
Sonneratia	Sonneratiaceae	15	0.5102
Vatica	Dipterocarpaceae	3	0.6734

APPENDIX C

CODE FOR SIMULATION MODEL

The code for the C-REC model (Chapter 4) is presented below. It is written in Quick Basic and was based on the format of FORMIX (Bossel & Krieger 1991).

```
DIM dia(2000), H(2000), stm(2000), brnch(2000), XX(2000), lf(2000), TotT(2000)
DECLARE SUB damage (injured!, N!, D!, AC!, AT!, AR!, LAI!, L!)
DECLARE SUB describe (CD!, N!, B!, BT!, D!, TR!, G!, F!, HD!, AC!, AT!, AR!, LAI!, L!)
DECLARE SUB die (M!, MB!, MS!, N!, BT!)
DECLARE SUB move (MD!, D!, TN!, TS!, N)
DECLARE SUB photo (Pmax, M, PS45, PS25, PS10, PS1, PSS, LAI45, LAI25, LAI10, LAI1, LAIS)
DECLARE SUB respire (PR, R, PS!, AT!, B!, Cgain!, litter)
DECLARE SUB seeding (survival, N45!, N25!, S!, TB0!)
DECLARE SUB setmortpers (switchA, ml, time, z, AR45, AR25, AR10, AR1, ARS, ms45, ms25, ms10, ms1,
msS)
DECLARE SUB setmortpion (time!, AR45!, AR25!, AR10!, AR1!, ARS!, ms45!, ms25!, ms10!, ms1!, msS!)
OPEN "c:\ril\model\test" FOR OUTPUT AS #16
RANDOMIZE TIMER
CLS
time = 0
LAI45 = 2 'these are the maximum values for each layer
LAI25 = 2
LAI10 = 2
LAI1 = 2
LAIS = 1
LAIP = 2 'pioneers have dense foliage - all layers same
Pmax = 15 'persistent species
M = .2
PR = .5
R = .06
PmaxP = 25 'pioneers
MP = .4
PRP = .35
RP = .06
TR = .7 'this is stemwood fraction
G = .516  'this is wood density
GP = .33  'for pioneer trees
CD = 25  'crown diameter
CDP = 32 'larger for pioneers
F45 = .38'these are form factors
F25 = .42'all from Bossel & Krieger
F10 = .44
F1 = .45
FS = .5
HD45 = 40 'this is height to diameter ratio
```

```
HD25 = 48 'from Bossel & Krieger
HD10 = 56
HD1 = 67
HDS = 140
HDP45 = 40  'these are guesses at what they might be
HDP25 = 48   'for pioneers
HDP10 = 56
HDP1 = 67
HDPS = 130
        'these are transition probabilities
TS25 = .02
TS10 = .05
TS1 = .08
TSS = .1
TSP25 = 1
TSP10 = 1
TSP1 = 1
TSPS = 1
survival = .5 'this is the standard seedling survival rate
ml = .05 'this is the elevated rate of mortality that follows logging, same for all layers
switchA = 5 'this is the duration of elevated mortality rates after logging
switchB = 5 'this switch is set so that persistent tree seedlings that establish
REM under pioneers do not experience the elevated mortality rates
DM25 = .45   'maximum diameters for each layer
DM10 = .25
DM1 = .1
DMS = .01    'add the necromass stores
          qc = 49.5   'standing stock CWD; Kira's average minus SWL
          qfl = 2.4  'standing stock fine litter Burghouts
         qswl = 2.5   'guess for small woody litter
         fldk = .71  'decay to atm Burghouts
         swldk = .454  'this is a guess
         ldktoS = .022 'decay to soil; Burghouts
         qcdk = .144 'Kira using 19% minus what wasn't coming off as CO2
         qctoS = .046 'Kira
         qsoil = 33 'Ohta & Effendi
REM removed  qsoilslow = 43  'standing stock, soil carbon, basically passive
         seflx = .05 'co2 efflux Kira as percent of soil om
        'read in data for "typical" hectare
        'for aboveground biomass, use five canopy layers
        'trees >45cm;25-45cm;10-25cm;1-10cm; seedlings
OPEN "c:\ril\model\GY45.txt" FOR INPUT AS #1
    WHILE NOT EOF(1)
        LINE INPUT #1, a$
        tno. = VAL(MID$(a$, 1, 5))
        dia(tno.) = VAL(MID$(a$, 17, 3))
    WEND
OPEN "c:\ril\model\GY2545.txt" FOR INPUT AS #2
    WHILE NOT EOF(2)
        LINE INPUT #2, B$
        tno. = VAL(MID$(B$, 1, 5))
        dia(tno.) = VAL(MID$(B$, 17, 3))
```

```
    WEND
OPEN "c:\ril\model\GY1025.txt" FOR INPUT AS #3
    WHILE NOT EOF(3)
        LINE INPUT #3, c$
        tno. = VAL(MID$(c$, 1, 5))
        dia(tno.) = VAL(MID$(c$, 17, 3))
    WEND
REM instead of an input file for saplings - I'll use pre-logging averages
REM the average number of trees 1-5 cm is 2891.2 with an avg dia of 2.42
REM the average number of trees 5-10 cm is 751 with an avg dia of 6.48
REM using the small tree biomass equation from our work you get the following
N1 = 2891 + 751
B1 = (3.429 + 9.355)   'calculate biomass per tree (>=10)
' height formula from Brown, Gillespie, & Lugo 1989 others Kira 1978
' branch biomass dropped down so that total biomass matches brown et al
tno. = 0
  FOR tno. = 1 TO 2000
    IF dia(tno.) >= 10 THEN
        H(tno.) = EXP(1.071 + .5677 * LOG(dia(tno.)))
        stm(tno.) = .313 * ((((dia(tno.) * .1) ^ 2) * (H(tno.) * 10)) ^ .9733)
        brnch(tno.) = .3 * (stm(tno.) ^ .98)
        XX(tno.) = (1 / (.124 * ((stm(tno.)) ^ .794))) + 1 / 125
        lf(tno.) = 1 / XX(tno.)
        TotT(tno.) = stm(tno.) + brnch(tno.) + lf(tno.)
    END IF
  NEXT            'calculate initial layer totals
tno. = 1
  FOR tno. = 1 TO 2000
        IF TotT(tno.) >= 1638 THEN
                B45 = TotT(tno.) + B45
                N45 = N45 + 1
        ELSEIF TotT(tno.) < 1638 AND TotT(tno.) > 383 THEN
                B25 = TotT(tno.) + B25
                N25 = N25 + 1
        ELSEIF TotT(tno.) <= 383 AND TotT(tno.) > 39 THEN
                B10 = TotT(tno.) + B10
                N10 = N10 + 1
        ELSE
        END IF
  NEXT tno.
B45 = B45 * .001
B25 = B25 * .001
B10 = B10 * .001
CALL describe(CD, N45, B45, BT45, D45, TR, G, F45, HD45, AC45, AT45, AR45, LAI45, L45)
CALL describe(CD, N25, B25, BT25, D25, TR, G, F25, HD25, AC25, AT25, AR25, LAI25, L25)
CALL describe(CD, N10, B10, BT10, D10, TR, G, F10, HD10, AC10, AT10, AR10, LAI10, L10)
CALL describe(CD, N1, B1, BT1, D1, TR, G, F1, HD1, AC1, AT1, AR1, LAI1, L1)
'    BT is biomass per tree        D is average diameter
'    AC is actual crown area       AT is current crown fill ratio
'    AR is crown closure deficit   XAT is maximum relative crown area
'    L is actual leaf area index   N is number of trees per layer
'    B is total biomass per layer
```

```
                'Initial Seedling Layer
BS = 2  ' clip plot minus some
NS = 14000 ' guess
CALL describe(CD, NS, BS, BTS, DS, TR, G, FS, HDS, ACS, ATS, ARS, LAIS, LS)
tbag = B45 + B25 + B10 + B1 + BS
PRINT "How many years would you like the model to run?"
INPUT duration
                'next section is for logging
150
PRINT "If logging, ENTER 1, otherwise ENTER 0"
INPUT z
IF z = 0 GOTO 550 ELSE
PRINT "What volume of timber was removed (cubic meters per ha)?"
INPUT VOL 'specific gravity = .516, converted from cubic meters to kg
Timber = VOL * .516
        IF Timber > B45 THEN
            brake = 1
            GOTO 500
        END IF
TreeDebris = 1.895 * Timber - Timber'this is using Brown et al's BEF
NumberFelled = (Timber + TreeDebris) / BT45
B45 = B45 - Timber - TreeDebris
N45 = N45 - NumberFelled
CALL describe(CD, N45, B45, BT45, D45, TR, G, F45, HD45, AC45, AT45, AR45, LAI45, L45)
qcfall = TreeDebris * .8    'these are guesses at proportional allocation
qswlfall = TreeDebris * .1
qflfall = TreeDebris * .1
PRINT "What proportion of the area was covered with soil disturbance?"
INPUT AST
        IF AST >= 1 THEN 'in case entered incorrectly
            brake = 1
            GOTO 500
        END IF ' this will set survival under pioneers
PRINT "what proportion of the residual stand was fatally damaged?"
INPUT DAMF
switch1 = 2 'this is when the pioneer seedlings establish in % area DAMF
switch2 = 5 'this is when persistent seedlings begin to establish under pioneers
        IF DAMF > 1 THEN
            brake = 1
            GOTO 500
        END IF
        IF DAMF < AST THEN DAMF = AST
TreeDebris = B45 * DAMF
B45 = B45 - TreeDebris
NumberKilled = TreeDebris / BT45
N45 = N45 - NumberKilled
CALL describe(CD, N45, B45, BT45, D45, TR, G, F45, HD45, AC45, AT45, AR45, LAI45, L45)
qcfall = qcfall + .8 * TreeDebris
qswlfall = qswlfall + .1 * TreeDebris
qflfall = qflfall + .1 * TreeDebris

TreeDebris = B25 * DAMF
```

```
B25 = B25 - TreeDebris
NumberKilled = TreeDebris / BT25
N25 = N25 - NumberKilled
CALL describe(CD, N25, B25, BT25, D25, TR, G, F25, HD25, AC25, AT25, AR25, LAI25, L25)
qcfall = qcfall + .75 * TreeDebris
qswlfall = qswlfall + .15 * TreeDebris
qflfall = qflfall + .1 * TreeDebris

TreeDebris = B10 * DAMF
B10 = B10 - TreeDebris
NumberKilled = TreeDebris / BT10
N10 = N10 - NumberKilled
CALL describe(CD, N10, B10, BT10, D10, TR, G, F10, HD10, AC10, AT10, AR10, LAI10, L10)
qcfall = qcfall + .5 * TreeDebris
qswlfall = qswlfall + .3 * TreeDebris
qflfall = qflfall + .2 * TreeDebris

TreeDebris = B1 * DAMF
B1 = B1 - TreeDebris
NumberKilled = TreeDebris / BT1
N1 = N1 - NumberKilled
CALL describe(CD, N1, B1, BT1, D1, TR, G, F1, HD1, AC1, AT1, AR1, LAI1, L1)
qswlfall = qswlfall + .8 * TreeDebris
qflfall = qflfall + .2 * TreeDebris

TreeDebris = BS * DAMF
BS = BS - TreeDebris
NumberKilled = TreeDebris / BTS
CALL describe(CD, NS, BS, BTS, DS, TR, G, FS, HDS, ACS, ATS, ARS, LAIS, LS)
qflfall = qflfall + TreeDebris

350
PRINT "What proportion of the remaining trees receive damage?"
INPUT injured
        IF injured + DAMF > 1 THEN
            brake = 1
            PRINT "you've damaged more than 100% of the trees!"
            PRINT "to go on, type 500"
            INPUT ok
                IF ok = 500 THEN
                    GOTO 500
                ELSE
                    GOTO 60000
                END IF
        END IF 'decrease crown area of damaged trees by 25%
CALL damage(injured, N45, D45, AC45, AT45, AR45, LAI45, L45)
CALL damage(injured, N25, D25, AC25, AT25, AR25, LAI25, L25)
CALL damage(injured, N10, D10, AC10, AT10, AR10, LAI10, L10)
CALL damage(injured, N1, D1, AC1, AT1, AR1, LAI1, L1)
CALL damage(injured, NS, DS, ACS, ATS, ARS, LAIS, LS)
500
IF brake = 1 GOTO 59999
```

```
IF brake = 2 THEN GOTO 575
      'here need to set up the pioneer tree forest; everything set at zero
CALL describe(CDP, NP45, BP45, BTP45, DP45, TR, GP, F45, HDP45, ACP45, ATP45, ARP45, LAIP,
LP45)
CALL describe(CDP, NP25, BP25, BTP25, DP25, TR, GP, F25, HDP25, ACP25, ATP25, ARP25, LAIP,
LP25)
CALL describe(CDP, NP10, BP10, BTP10, DP10, TR, GP, F10, HDP10, ACP10, ATP10, ARP10, LAIP,
LP10)
CALL describe(CDP, NP1, BP1, BTP1, DP1, TR, GP, F1, HD1, ACP1, ATP1, ARP1, LAIP, LP1)
CALL describe(CDP, NPS, BPS, BTPS, DPS, TR, GP, FS, HDPS, ACPS, ATPS, ARPS, LAIP, LPS)
550
575
time = time + 1
       'determine Gross and Net photosynthetic production
CALL photo(Pmax, M, PS45, PS25, PS10, PS1, PSS, L45, L25, L10, L1, LS)
CALL photo(PmaxP, MP, PSP45, PSP25, PSP10, PSP1, PSPS, LP45, LP25, LP10, LP1, LPS)
    'any variable with a P on the end represents pioneers
    'any variable with a PD represents persistent species coming in under pioneers
    ' this next set of commands allows the persistents under pioneers to photosynthesize
    'meant to provide shading from above (pioneer tree Leaf Area)
     IF z = 1 THEN
     SELECT CASE time
          CASE 4 TO 6 ' during these years pioneers in layer 1-10 cm dbh
               CALL photo(Pmax, M, PSPD45, PSPD25, PSPD10, PSPD1, PSPDS, LP45, LP25, LP10, LP1,
LPDS)
          CASE 7 TO 9'during these years pioneers are in layer 10-25 cm dbh
               CALL photo(Pmax, M, PSPD45, PSPD25, PSPD10, PSPD1, PSPDS, LP45, LP25, LP10,
LPD1, LPDS)
          CASE 10 TO 15'during these years pioneers are in layer 25-45 cm dbh
               CALL photo(Pmax, M, PSPD45, PSPD25, PSPD10, PSPD1, PSPDS, LP45, LP25, LPD10,
LPD1, LPDS)
          CASE IS >= 16
               CALL photo(Pmax, M, PSPD45, PSPD25, PSPD10, PSPD1, PSPDS, LPD45, LPD25, LPD10,
LPD1, LPDS)
          CASE ELSE
     END SELECT
     END IF
'remove stem respiration, leaf and root respiration
     'some of the efficiency described in PR values represents litterfall
CALL respire(PR, R, PS45, AT45, B45, Cgain45, litter45)
CALL respire(PR, R, PS25, AT25, B25, Cgain25, litter25)
CALL respire(PR, R, PS10, AT10, B10, Cgain10, litter10)
CALL respire(PR, R, PS1, AT1, B1, Cgain1, litter1)
CALL respire(PR, R, PSS, ATS, BS, CgainS, litterS)

CALL respire(PRP, RP, PSP45, ATP45, BP45, CgainP45, litterP45)
CALL respire(PRP, RP, PSP25, ATP25, BP25, CgainP25, litterP25)
CALL respire(PRP, RP, PSP10, ATP10, BP10, CgainP10, litterP10)
CALL respire(PRP, RP, PSP1, ATP1, BP1, CgainP1, litterP1)
CALL respire(PRP, RP, PSPS, ATPS, BPS, CgainPS, litterPS)

CALL respire(PR, R, PSPD45, ATPD45, BPD45, CgainPD45, litterPD45)
```

```
CALL respire(PR, R, PSPD25, ATPD25, BPD25, CgainPD25, litterPD25)
CALL respire(PR, R, PSPD10, ATPD10, BPD10, CgainPD10, litterPD10)
CALL respire(PR, R, PSPD1, ATPD1, BPD1, CgainPD1, litterPD1)
CALL respire(PR, R, PSPDS, ATPDS, BPDS, CgainPDS, litterPDS)
    'all of the litter will be split into fractions at the end of the year
IF z = 0 THEN debrisfall = litter45 + litter25 + litter10 + litter1 + litterS
IF z = 1 THEN
    debrisfall = (1 - DAMF) * (litter45 + litter25 + litter10 + litter1 + litterS)
    debrisfall = debrisfall + DAMF * (litterP45 + litterP25 + litterP10 + litterP1 + litterPS)
    debrisfall = debrisfall + DAMF * (litterPD45 + litterPD25 + litterPD10 + litterPD1 + litterPDS)
END IF
    'add Cgain to layer totals and recalculate descriptive parameters
B45 = B45 + Cgain45
B25 = B25 + Cgain25
B10 = B10 + Cgain10
B1 = B1 + Cgain1
BS = BS + CgainS

BP45 = BP45 + CgainP45
BP25 = BP25 + CgainP25
BP10 = BP10 + CgainP10
BP1 = BP1 + CgainP1
BPS = BPS + CgainPS

BPD45 = BPD45 + CgainPD45
BPD25 = BPD25 + CgainPD25
BPD10 = BPD10 + CgainPD10
BPD1 = BPD1 + CgainPD1
BPDS = BPDS + CgainPDS

Cgain = Cgain45 + Cgain25 + Cgain10 + Cgain1 + CgainS
CgainPio = CgainP45 + CgainP25 + CgainP10 + CgainP1 + CgainPS
CgainPD = CgainPD45 + CgainPD25 + CgainPD10 + CgainPD1 + CgainPDS
            REM add new seedlings
CALL seeding(survival, N45!, N25!, S!, TB0!)
BS = BS + TB0
NS = NS + S
IF z = 1 THEN
        SELECT CASE time
            CASE IS = switch1
                NPS = 13500 'pioneers seed once
                BPS = 1.25
            CASE IS >= switch2
'only a portion of residuals are allowed to seed, as damage increases, portion seeding decreases
                seed45 = N45 * ((1 - DAMF) ^ 2)
                seed25 = N25 * ((1 - DAMF) ^ 2)
                survPD = survival * (1 - AST) 'now a fx of skid trail area
                CALL seeding(survPD, seed45, seed25, SPD, TPD0)
                NPDS = SPD + NPDS
                BPDS = TPD0 + BPDS
   'also get seeding beneath these persistent spp under pioneers
                CALL seeding(survPD, NPD45, NPD25, SPD, TPD0)
```

```
                    BPDS = BPDS + TPD0
                    NPDS = NPDS + SPD
                CASE ELSE
            END SELECT
END IF
    'these describe the residual forest species/unlogged forest
CALL describe(CD, N45, B45, BT45, D45, TR, G, F45, HD45, AC45, AT45, AR45, LAI45, L45)
CALL describe(CD, N25, B25, BT25, D25, TR, G, F25, HD25, AC25, AT25, AR25, LAI25, L25)
CALL describe(CD, N10, B10, BT10, D10, TR, G, F10, HD10, AC10, AT10, AR10, LAI10, L10)
CALL describe(CD, N1, B1, BT1, D1, TR, G, F1, HD1, AC1, AT1, AR1, LAI1, L1)
CALL describe(CD, NS, BS, BTS, DS, TR, G, FS, HDS, ACS, ATS, ARS, LAIS, LS)
    'these describe the pioneers
CALL describe(CDP, NP45, BP45, BTP45, DP45, TR, GP, F45, HDP45, ACP45, ATP45, ARP45, LAIP,
LP45)
CALL describe(CDP, NP25, BP25, BTP25, DP25, TR, GP, F25, HDP25, ACP25, ATP25, ARP25, LAIP,
LP25)
CALL describe(CDP, NP10, BP10, BTP10, DP10, TR, GP, F10, HDP10, ACP10, ATP10, ARP10, LAIP,
LP10)
CALL describe(CDP, NP1, BP1, BTP1, DP1, TR, GP, F1, HDP1, ACP1, ATP1, ARP1, LAIP, LP1)
CALL describe(CDP, NPS, BPS, BTPS, DPS, TR, GP, FS, HDPS, ACPS, ATPS, ARPS, LAIP, LPS)
    'these describe the persistents under the pioneers
CALL describe(CD, NPD45, BPD45, BTPD45, DPD45, TR, G, F45, HD45, ACPD45, ATPD45, ARPD45,
LAI45, LPD45)
CALL describe(CD, NPD25, BPD25, BTPD25, DPD25, TR, G, F25, HD25, ACPD25, ATPD25, ARPD25,
LAI25, LPD25)
CALL describe(CD, NPD10, BPD10, BTPD10, DPD10, TR, G, F10, HD10, ACPD10, ATPD10, ARPD10,
LAI10, LPD10)
CALL describe(CD, NPD1, BPD1, BTPD1, DPD1, TR, G, F1, HD1, ACPD1, ATPD1, ARPD1, LAI1,
LPD1)
CALL describe(CD, NPDS, BPDS, BTPDS, DPDS, TR, G, FS, HDS, ACPDS, ATPDS, ARPDS, LAIS,
LPDS)
                REM transitions
    'these move the persistent species in the residual forest
CALL move(DM25, D25, TN25, TS25, N25)
CALL move(DM10, D10, TN10, TS10, N10)
CALL move(DM1, D1, TN1, TS1, N1)
CALL move(DMS, DS, TNS, TSS, NS)
    'these move the pioneers
CALL move(DM25, DP25, TNP25, TSP25, NP25)
CALL move(DM10, DP10, TNP10, TSP10, NP10)
CALL move(DM1, DP1, TNP1, TSP1, NP1)
CALL move(DMS, DPS, TNPS, TSPS, NPS)
    'these move the persistents under the pioneers
CALL move(DM25, DPD25, TNPD25, TS25, NPD25)
CALL move(DM10, DPD10, TNPD10, TS10, NPD10)
CALL move(DM1, DPD1, TNPD1, TS1, NPD1)
CALL move(DMS, DPDS, TNPDS, TSS, NPDS)
            REM now tally new numbers
    'these are for the residual trees
N45 = N45 + TN25
N25 = N25 + TN10 - TN25
N10 = N10 + TN1 - TN10
```

```
N1 = N1 + TNS - TN1
NS = NS - TNS
B45 = B45 + TN25 * BT25
B25 = B25 + TN10 * BT10 - TN25 * BT25
B10 = B10 + TN1 * BT1 - TN10 * BT10
B1 = B1 + TNS * BTS - TN1 * BT1
BS = BS - TNS * BTS
    'these are for the  pioneers
NP45 = NP45 + TNP25
NP25 = NP25 + TNP10 - TNP25
NP10 = NP10 + TNP1 - TNP10
NP1 = NP1 + TNPS - TNP1
NPS = NPS - TNPS
BP45 = BP45 + TNP25 * BTP25
BP25 = BP25 + TNP10 * BTP10 - TNP25 * BTP25
BP10 = BP10 + TNP1 * BTP1 - TNP10 * BTP10
BP1 = BP1 + TNPS * BTPS - TNP1 * BTP1
BPS = BPS - TNPS * BTPS
    'these are for the persistent species under the pioneers
NPD45 = NPD45 + TNPD25
NPD25 = NPD25 + TNPD10 - TNPD25
NPD10 = NPD10 + TNPD1 - TNPD10
NPD1 = NPD1 + TNPDS - TNPD1
NPDS = NPDS - TNPDS
BPD45 = BPD45 + TNPD25 * BTPD25
BPD25 = BPD25 + TNPD10 * BTPD10 - TNPD25 * BTPD25
BPD10 = BPD10 + TNPD1 * BTPD1 - TNPD10 * BTPD10
BPD1 = BPD1 + TNPDS * BTPDS - TNPD1 * BTPD1
BPDS = BPDS - TNPDS * BTPDS
    'these describe residual trees
CALL describe(CD, N45, B45, BT45, D45, TR, G, F45, HD45, AC45, AT45, AR45, LAI45, L45)
CALL describe(CD, N25, B25, BT25, D25, TR, G, F25, HD25, AC25, AT25, AR25, LAI25, L25)
CALL describe(CD, N10, B10, BT10, D10, TR, G, F10, HD10, AC10, AT10, AR10, LAI10, L10)
CALL describe(CD, N1, B1, BT1, D1, TR, G, F1, HD1, AC1, AT1, AR1, LAI1, L1)
CALL describe(CD, NS, BS, BTS, DS, TR, G, FS, HDS, ACS, ATS, ARS, LAIS, LS)
    'these describe pioneer trees
CALL describe(CDP, NP45, BP45, BTP45, DP45, TR, GP, F45, HDP45, ACP45, ATP45, ARP45, LAIP,
LP45)
CALL describe(CDP, NP25, BP25, BTP25, DP25, TR, GP, F25, HDP25, ACP25, ATP25, ARP25, LAIP,
LP25)
CALL describe(CDP, NP10, BP10, BTP10, DP10, TR, GP, F10, HDP10, ACP10, ATP10, ARP10, LAIP,
LP10)
CALL describe(CDP, NP1, BP1, BTP1, DP1, TR, GP, F1, HD1, ACP1, ATP1, ARP1, LAIP, LP1)
CALL describe(CDP, NPS, BPS, BTPS, DPS, TR, GP, FS, HDPS, ACPS, ATPS, ARPS, LAIP, LPS)
    'these describe the persistents under the pioneers
CALL describe(CD, NPD45, BPD45, BTPD45, DPD45, TR, G, F45, HD45, ACPD45, ATPD45, ARPD45,
LAI45, LPD45)
CALL describe(CD, NPD25, BPD25, BTPD25, DPD25, TR, G, F25, HD25, ACPD25, ATPD25, ARPD25,
LAI25, LPD25)
CALL describe(CD, NPD10, BPD10, BTPD10, DPD10, TR, G, F10, HD10, ACPD10, ATPD10, ARPD10,
LAI10, LPD10)
CALL describe(CD, NPD1, BPD1, BTPD1, DPD1, TR, G, F1, HD1, ACPD1, ATPD1, ARPD1, LAI1,
```

```
LPD1)
CALL describe(CD, NPDS, BPDS, BTPDS, DPDS, TR, G, FS, HDS, ACPDS, ATPDS, ARPDS, LAIS,
LPDS)
        REM determine mortality rates and kill trees
CALL setmortpers(switchA, ml, time, z, AR45, AR25, AR10, AR1, ARS, ms45, ms25, ms10, ms1, msS)
CALL setmortpion(time, ARP45, ARP25, ARP10, ARP1, ARPS, msP45, msP25, msP10, msP1, msPS)
CALL setmortpers(switchB, ml, time, z, ARPD45, ARPD25, ARPD10, ARPD1, ARPDS, msPD45, msPD25,
msPD10, msPD1, msPDS)

CALL die(M45, MB45, ms45, N45, BT45)
CALL die(M25, MB25, ms25, N25, BT25)
CALL die(M10, MB10, ms10, N10, BT10)
CALL die(M1, MB1, ms1, N1, BT1)
CALL die(MS, MBS, msS, NS, BTS)

CALL die(MP45, MBP45, msP45, NP45, BTP45)
CALL die(MP25, MBP25, msP25, NP25, BTP25)
CALL die(MP10, MBP10, msP10, NP10, BTP10)
CALL die(MP1, MBP1, msP1, NP1, BTP1)
CALL die(MPS, MBPS, msPS, NPS, BTPS)

CALL die(MPD45, MBPD45, msPD45, NPD45, BTPD45)
CALL die(MPD25, MBPD25, msPD25, NPD25, BTPD25)
CALL die(MPD10, MBPD10, msPD10, NPD10, BTPD10)
CALL die(MPD1, MBPD1, msPD1, NPD1, BTPD1)
CALL die(MPDS, MBPDS, msPDS, NPDS, BTPDS)

'need new counts and biomass tallies // need to check for  zeroes
    IF M45 > N45 THEN M45 = N45
     N45 = N45 - M45
    IF M25 > N25 THEN M25 = N25
     N25 = N25 - M25
    IF M10 > N10 THEN M10 = N10
     N10 = N10 - M10
    IF M1 > N1 THEN M1 = N1
     N1 = N1 - M1
    IF MS > NS THEN MS = NS
     NS = NS - MS

    IF MB45 > B45 THEN MB45 = B45
     B45 = B45 - MB45
    IF MB25 > B25 THEN MB25 = B25
     B25 = B25 - MB25
    IF MB10 > B10 THEN MB10 = B10
     B10 = B10 - MB10
    IF MB1 > B1 THEN MB1 = B1
     B1 = B1 - MB1
    IF MBS > BS THEN MBS = BS
     BS = BS - MBS
'these are for pioneers
    IF MP45 > NP45 THEN MP45 = NP45
     NP45 = NP45 - MP45
```

```
    IF MP25 > NP25 THEN MP25 = NP25
     NP25 = NP25 - MP25
    IF MP10 > NP10 THEN MP10 = NP10
     NP10 = NP10 - MP10
    IF MP1 > NP1 THEN MP1 = NP1
     NP1 = NP1 - MP1
    IF MPS > NPS THEN MPS = NPS
     NPS = NPS - MPS

    IF MBP45 > BP45 THEN MBP45 = BP45
     BP45 = BP45 - MBP45
    IF MBP25 > BP25 THEN MBP25 = BP25
     BP25 = BP25 - MBP25
    IF MBP10 > BP10 THEN MBP10 = BP10
     BP10 = BP10 - MBP10
    IF MBP1 > BP1 THEN MBP1 = BP1
     BP1 = BP1 - MBP1
    IF MBPS > BPS THEN MBPS = BPS
     BPS = BPS - MBPS

'these are for the persistent under pioneers
    IF MPD45 > NPD45 THEN MPD45 = NPD45
     NPD45 = NPD45 - MPD45
    IF MPD25 > NPD25 THEN MPD25 = NPD25
     NPD25 = NPD25 - MPD25
    IF MPD10 > NPD10 THEN MPD10 = NPD10
     NPD10 = NPD10 - MPD10
    IF MPD1 > NPD1 THEN MPD1 = NPD1
     NPD1 = NPD1 - MPD1
    IF MPDS > NPDS THEN MPDS = NPDS
     NPDS = NPDS - MPDS

    IF MBPD45 > BPD45 THEN MBPD45 = BPD45
     BPD45 = BPD45 - MBPD45
    IF MBPD25 > BPD25 THEN MBPD25 = BPD25
     BPD25 = BPD25 - MBPD25
    IF MBPD10 > BPD10 THEN MBPD10 = BPD10
     BPD10 = BPD10 - MBPD10
    IF MBPD1 > BPD1 THEN MBPD1 = BPD1
     BPD1 = BPD1 - MBPD1
    IF MBPDS > BPDS THEN MBPDS = BPDS
     BPDS = BPDS - MBPDS

CALL describe(CD, N45, B45, BT45, D45, TR, G, F45, HD45, AC45, AT45, AR45, LAI45, L45)
CALL describe(CD, N25, B25, BT25, D25, TR, G, F25, HD25, AC25, AT25, AR25, LAI25, L25)
CALL describe(CD, N10, B10, BT10, D10, TR, G, F10, HD10, AC10, AT10, AR10, LAI10, L10)
CALL describe(CD, N1, B1, BT1, D1, TR, G, F1, HD1, AC1, AT1, AR1, LAI1, L1)
CALL describe(CD, NS, BS, BTS, DS, TR, G, FS, HDS, ACS, ATS, ARS, LAIS, LS)

CALL describe(CDP, NP45, BP45, BTP45, DP45, TR, GP, F45, HDP45, ACP45, ATP45, ARP45, LAIP,
LP45)
CALL describe(CDP, NP25, BP25, BTP25, DP25, TR, GP, F25, HDP25, ACP25, ATP25, ARP25, LAIP,
```

```
LP25)
CALL describe(CDP, NP10, BP10, BTP10, DP10, TR, GP, F10, HDP10, ACP10, ATP10, ARP10, LAIP,
LP10)
CALL describe(CDP, NP1, BP1, BTP1, DP1, TR, GP, F1, HD1, ACP1, ATP1, ARP1, LAIP, LP1)
CALL describe(CDP, NPS, BPS, BTPS, DPS, TR, GP, FS, HDPS, ACPS, ATPS, ARPS, LAIP, LPS)
     'these describe the persistents under the pioneers
CALL describe(CD, NPD45, BPD45, BTPD45, DPD45, TR, G, F45, HD45, ACPD45, ATPD45, ARPD45,
LAI45, LPD45)
CALL describe(CD, NPD25, BPD25, BTPD25, DPD25, TR, G, F25, HD25, ACPD25, ATPD25, ARPD25,
LAI25, LPD25)
CALL describe(CD, NPD10, BPD10, BTPD10, DPD10, TR, G, F10, HD10, ACPD10, ATPD10, ARPD10,
LAI10, LPD10)
CALL describe(CD, NPD1, BPD1, BTPD1, DPD1, TR, G, F1, HD1, ACPD1, ATPD1, ARPD1, LAI1,
LPD1)
CALL describe(CD, NPDS, BPDS, BTPDS, DPDS, TR, G, FS, HDS, ACPDS, ATPDS, ARPDS, LAIS,
LPDS)
      'debris from these trees goes into necromass pools
      'use allocation to sizeclasses as was used in logging
      'also add in debrisfall from logging activities
IF z = 0 THEN
    qflfall = qflfall + MBS + .2 * MB1 + .2 * MB10 + .1 * MB25 + .1 * MB45
    qflfall = qflfall + .74 * debrisfall
    qswlfall = qswlfall + .8 * MB1 + .3 * MB10 + .15 * MB25 + .1 * MB45
    qswlfall = qswlfal + .26 * debrisfall
    qcfall = qcfall + .5 * MB10 + .75 * MB25 + .8 * MB45
END IF

IF z = 1 THEN
    qflfall = qflfall + (MBS * (1 - DAMF)) + (DAMF * (MBPS + MBPDS))
    qflfall = qflfall + (.2 * (MB1 * (1 - DAMF))) + (.2 * (DAMF * (MBP1 + MBPD1)))
    qflfall = qflfall + (.2 * (MB10 * (1 - DAMF))) + (.2 * (DAMF * (MBP10 + MBPD10)))
    qflfall = qflfall + (.1 * (MB25 * (1 - DAMF))) + (.1 * (DAMF * (MBP25 + MBPD25)))
    qflfall = qflfall + (.1 * (MB45 * (1 - DAMF))) + (.1 * (DAMF * (MBP45 + MBPD45)))
    qflfall = qflfall + debrisfall * .74
    qswlfall = qswlfall + (.8 * (MB1 * (1 - DAMF))) + (.8 * (DAMF * (MBP1 + MBPD1)))
    qswlfall = qswlfall + (.3 * (MB10 * (1 - DAMF))) + (.3 * (DAMF * (MBP10 + MBPD10)))
    qswlfall = qswlfall + (.15 * (MB25 * (1 - DAMF))) + (.15 * (DAMF * (MBP25 + MBPD25)))
    qswlfall = qswlfall + (.1 * (MB45 * (1 - DAMF))) + (.1 * (DAMF * (MBP45 + MBPD45)))
    qswlfall = qswlfal + .26 * debrisfall
    qcfall = qcfall + (.5 * (MB10 * (1 - DAMF))) + (.5 * (DAMF * (MBP10 + MBPD10)))
    qcfall = qcfall + (.75 * (MB25 * (1 - DAMF))) + (.75 * (DAMF * (MBP25 + MBPD25)))
    qcfall = qcfall + (.8 * (MB45 * (1 - DAMF))) + (.8 * (DAMF * (MBP45 + MBPD45)))
END IF
        Residfor = B45 + B25 + B10 + B1 + BS
        Pionfor = BP45 + BP25 + BP10 + BP1 + BPS
        pd = BPD45 + BPD25 + BPD10 + BPD1 + BPDS
        Pfor = Pionfor + pd
        tbag = (Residfor * (1 - DAMF)) + (Pfor * DAMF)
qc = qc + qcfall
qsoil = qsoil + qctoS * qc * .5 'from Kira, Yoneda, Yoda decay from CWD minus CO2 evolved
qc = qc - qc * (qcdk + qctoS)'Kira's net annual percent loss in mass
qfl = qfl + qflfall
```

```
qsoil = qsoil + ldktoS * qfl * .469
qfl = qfl - ldktoS * qfl - fldk * qfl
qswl = qswl + qswlfall
qsoil = qsoil + qctoS * qswl * .5
qswl = qswl - swldk * qswl - qswl * qctoS
qsoil = qsoil - seflx * qsoil
allcarbon = (tbag * .5) + qsoil + qswl * .5 + qfl * .469 + qc * .5
necromass = qsoil + qc * .5 + qfl * .469 + qswl * .5
cummC = allcarbon + cummC
cummBio = tbag + cummBio
qflfall = 0
qswlfall = 0
qcfall = 0
debrisfall = 0
IF time = 20 THEN
    PRINT "Pioneer forest at 20 yrs is"; Pionfor
  ' PRINT "pd is"; pd
    PRINT "mean total C at 20 yrs is"; cummC / 20
    PRINT "mean tbag at 20 yrs is"; cummBio / 20
    PRINT "end tbag at 20 yrs is"; tbag
END IF

IF time = 40 THEN
      PRINT "mean total C at 40 yrs is"; cummC / 40
      'PRINT "end C at 40 yrs is"; allcarbon
      PRINT "mean tbag at 40 yrs"; cummBio / 40
      'PRINT "no. of big trees is"; N45 + NPD45
END IF
IF time < duration GOTO 575
IF time >= duration THEN
     PRINT "mean total C at 60 is"; cummC / duration
    ' PRINT "end total C at 60 is"; allcarbon
     PRINT "endB45 at 60 yrs is"; B45 * (1 - DAMF) + BPD45 * DAMF
     ' PRINT "ending no. B45 is"; N45 * (1 - DAMF) + NPD45 * DAMF
     ' PRINT "pd is"; pd
     ' PRINT "no. of big trees is"; N45 + NPD45
    GOTO 60000
END IF

59999    PRINT "not enough big trees or problem with input for disturbance"
60000 END

SUB damage (injured, N, D, AC, AT, AR, LAI, L)
Hurt = injured * N
AC = 3.14159 / 4 * ((25 * D) ^ 2)
ACHurt = AC * .75
XAT = ((AC * (N - Hurt)) + (ACHurt * Hurt)) / 10000
AR = 1 - XAT
IF AR > 0 THEN
     AT = XAT
ELSE
     AT = 1
```

```
END IF
L = AT * LAI
END SUB

SUB describe (CD, N, B, BT, D, TR, G, F, HD, AC, AT, AR, LAI, L)
IF B < 0 THEN B = 0
IF N < 0 THEN N = 0
IF N > 0 THEN
    BT = B / N
ELSE
    BT = 0
END IF
D = ((4 * BT * TR) / (3.14159 * G * F * HD)) ^ .3333
H = D * HD
AC = 3.14159 / 4 * ((CD * D) ^ 2)
XAT = AC * N / 10000
AR = 1 - XAT
IF AR > 0 THEN
    AT = XAT
ELSE
    AT = 1
END IF
L = AT * LAI
END SUB

SUB die (M, MB, MS, N, BT)
M = MS * N
MB = M * BT
END SUB

SUB move (MD, D, TN, TS, N)
XT = N * TS
DD = MD - D
IF DD > 0 THEN
    TN = 0
ELSE
    TN = XT
END IF
END SUB

SUB photo (Pmax, M, PS45, PS25, PS10, PS1, PSS, LAI45, LAI25, LAI10, LAI1, LAIS) STATIC
'this subroutine calculates gross ps rate by layer; based on Kira, Bossel and Krieger
i = 335
K45 = .86   'from Vertical stratification//Martin's ref.
K25 = .86   'this reflects leaf orientation
K10 = .54
K1 = .54
KS = 1      'understory leaves are flat
I45 = i
I25 = I45 * EXP(-K45 * LAI45)
I10 = I25 * EXP(-K25 * LAI25)
I1 = I10 * EXP(-K10 * LAI10)
```

```
ISS = I1 * EXP(-K1 * LAI1)
c = 2.39
PS45 = c * (Pmax / K45) * LOG((1 + (M / Pmax) * I45) / (1 + (M / Pmax) * I25))
PS25 = c * (Pmax / K25) * LOG((1 + (M / Pmax) * I25) / (1 + (M / Pmax) * I10))
PS10 = c * (Pmax / K10) * LOG((1 + (M / Pmax) * I10) / (1 + (M / Pmax) * I1))
PSI = c * (Pmax / KI) * LOG((1 + (M / Pmax) * I1) / (I + (M / Pmax) * ISS))
PSS = c * (Pmax / KS) * LOG((1 + (M / Pmax) * ISS) / (1 + (M / Pmax) * ISS * EXP(-KS * LAIS)))
END SUB

SUB respire (PR, R, PS, AT, B, Cgain, litter)
PT = PS * AT 'multiplies ps by foliage
PB = PT * PR      ' multiplies ps gain by effic. (=leaf&root resp)
litter = PT * .15
Cgain = PB - (R * B)   'removes stem respiration
IF Cgain < 0 THEN Cgain = 0
END SUB

SUB seeding (survival, N45!, N25!, S!, TB0!)
' this subroutine is based on Bossel & Krieger for adding new dipterocarp recruits
REM  would like to make this reflect c vs n and 5yr intervals
SP = 1000 * survival
S = (N45 + N25) * SP
seedlingbio = .00002'equivalent to 20 grams
TB0 = seedlingbio * S
END SUB

SUB setmortpers (switch, ml, time, z, AR45, AR25, AR10, AR1, ARS, ms45, ms25, ms10, ms1, msS)
REM tree mortality      all based on Bossel & Krieger
    mn45 = .005
    mn25 = .008
    mn10 = .01
    mn1 = .005
    mnS = .1
    mc45 = .1
    mc25 = .15
    mc10 = .2
    mc1 = .5
    mcS = .5
        IF AR45 <= 0 THEN
            ms45 = mc45
        ELSEIF z = 1 THEN 'set up so that mortality is elevated after logging
            IF time <= switch THEN
                ms45 = ml
            END IF
            IF time > switch THEN
                ms45 = mn45
            END IF
        ELSE
            ms45 = mn45
        END IF

        IF AR25 <= 0 THEN
```

```
            ms25 = mc25
        ELSEIF z = 1 THEN
            IF time <= switch THEN
                ms25 = ml
            END IF
            IF time > switch THEN
                ms25 = mn25
            END IF
        ELSE
            ms25 = mn25
        END IF

        IF AR10 <= 0 THEN
            ms10 = mc10
        ELSEIF z = 1 THEN
            IF time <= switch THEN
                ms10 = ml
            END IF
            IF time > switch THEN
                ms10 = mn10
            END IF
        ELSE
            ms10 = mn10
        END IF

        IF AR1 <= 0 THEN
            ms1 = mc1
        ELSEIF z = 1 THEN
            IF time <= switch THEN
            ms1 = ml
            END IF
            IF time > switch THEN
                ms1 = mn1
            END IF
        ELSE
            ms1 = mn1
        END IF

        IF ARS <= 0 THEN
            msS = mcS
        ELSE
            msS = mnS
        END IF
END SUB

SUB setmortpion (time, AR45, AR25, AR10, AR1, ARS, ms45, ms25, ms10, ms1, msS)
    mn45 = .01
    mn25 = .01
    mn10 = .05
    mn1 = .05
    mnS = .1
    mc45 = .25
```

```
mc25 = .25
mc10 = .25
mc1 = .5
mcS = .5

    IF AR45 <= 0 THEN
        ms45 = mc45
    ELSEIF time > 30 THEN
        ms45 = .5
    ELSE
        ms45 = mn45
    END IF

    IF AR25 <= 0 THEN
        ms25 = mc25
    ELSEIF time > 30 THEN
        ms25 = .33
    ELSE
        ms25 = mn25
    END IF


    IF AR10 <= 0 THEN
        ms10 = mc10
    ELSEIF time > 30 THEN
        ms10 = .33
    ELSE
        ms10 = mn10
    END IF


    IF AR1 <= 0 THEN
        ms1 = mc1
    ELSEIF time > 30 THEN
        ms1 = mc1
    ELSEIF time < 4 THEN
        ms1 = mc1
    ELSE
        ms1 = mn1
    END IF

    IF ARS <= 0 THEN
        msS = mcS
    ELSEIF time < 5 THEN
        msS = mcS
    ELSE
        msS = mnS
    END IF
END SUB
```

APPENDIX D

FLOW CHART FOR SIMULATION MODEL

In the following outline I summarize the procedures used in the C-REC model (Chapter 4; Appendix C).

I. Setup

- A. Read in subroutines
- B. Read in set variables
  1. maximum LAI, physiological attributes
  2. stemwood fraction, wood densities, crown diameter ratio
  3. form factors, height-diameter relationships
  4. transition probabilities, seedling survival rate
  5. maximum diameters
  6. initial necromass conditions and coefficients
- C. Read in data for stand structure in one hectare
  1. 3 files for 3 canopy layers (>45 cm, 25-45 cm, 10-25 cm dbh)
     - a. each tree has - [tree no.; dbh]
     - b. calculate biomass for each tree
     - c. initial conditions all trees are nonpioneers
     - d. uses equations that are hybrids between Kira's and Brown et al.
  2. for lower 2 layers - seedlings and saplings (1-10 cm dbh)
     - a. tree numbers and biomass figures based on Ulu Segama data

D. Calculate totals to describe the layers [sub describe]

1. number, total biomass, biomass per tree, avg diameter, height

2. crown projection area, leaf area, leaf area index

II. Input - how many years will the model run? DURATION

III. Input - is there logging? - if yes Z = 1

A. enter volume of timber removed VOL

1. convert volume to biomass

2. calculate treedebris produced from trees felled

3. put debris into necromass pools (80% cwd; 10% swl; 10% fl)

4. remove biomass for timber from upper layer

5. remove the number of trees felled from total

6. recalculate totals to describe the layer

B. enter area covered with soil disturbance [sets seedling survival rates in disturbed forest area]

C. enter proportion of trees fatally damaged

1. kill this proportion of the trees and biomass in each layer

a. proportion of total now TreeDebris, Numberkilled

b. subtract from totals, recalculate layers

c. add to necromass pools

(1) for trees >45 cm dbh (80% cwd; 10% swl; 10% fl)

(2) for trees 25-45 cm dbh (75% cwd; 15% swl; 10% fl)

(3) for trees 10-25 cm dbh (50% cwd; 30% swl; 20% fl)

(4) for trees 1-10 cm dbh (80% swl; 20% fl)

(5) for seedlings (100% fl)

2. this proportion of area will be pioneers

D. set switches - time when pioneers seed in, persistent forest species seed in under pioneers

E. enter proportion of trees damaged but not fatally [decrease crown area by 25%]

1. determine number of trees hurt

2. calculate the area of crown if only 75% of normal

3. calculate layer total with proportion at 75% crownarea

4. calculate layer LAI based on change

F. set up initial conditions for Pioneer tree forest [all set to zero]

G. Return to Program, time set $t_0 = 0$

IV. Is there logging? if no ------------- Z = 0

A. Forest starts to grow - Residual Forest and Pioneer Forest

1. determine gross Ps per layer - [sub photopers and photopion]

a. uses actual LAI per layer, light extinction coefficients, Pmax, M

b. C - from Bossel & Krieger to go from photoproduction to organic matter

c. Photopers and photopion same structure but different Pmax, M values

2. determine losses to respiration and litterfall [sub respers. and respion]

3. allocate C gain to layers

B. Seeding

1. new seedlings based on number of trees >25 cm dbh, biomass per seedling constant

2. if logging

a. pioneers seed in once at 1 year after logging (switch1)

b. persistent species seed in under pioneers at 5 years after logging (switch2)

c. seed rain from residuals influenced by damage

(1) no. of seed trees = no. * (1-proportion stand with fatal damage)^2

d. seedling survival influenced by area with soil disturbance

(1) survival rate = standard rate * (1-area with soil disturbance)

e. persistent species seed under themselves (switch3)

3. recalculate totals by layer

C. Determine transitions

1. compare average diameter per layer with the maximum

2. if avg > max, transfer seedlings based on transition probabilities

3. transfer both numbers and biomass

4. recalculate totals by layer

D. Mortality

1. determine mortality rates based on crowding [sub setmortpers, setmortpion]

a. dependent on layer total stem biomass, leaf area, time after logging

b. elevated for 5 yr after logging

c. pioneer forest dies out at 30 years

2. kill trees and put in necromass

3. distribute debrisfall and mortality to pools

4. recalculate newlayer totals

E. Describe logged forest, if appropriate

1. Pioneer forest occupies proportion in fatal damage

2. Residual forest occupies area that was not damaged (1-DAMF) for 30 yrs

3. Recalculate totals based on proportional representation of these areas

F. Necromass dynamics [lose some to decay; transfer some to soil]

G. Increment time t = t + 1

H. If time < Duration go to V (above).

I. If time => Duration end.

APPENDIX E

SENSITIVITY ANALYSIS RESULTS

Sensitivity analyses were run for a no logging scenario (Table E-1) and a logging scenario (Table E-2). The listed variables, parameters, and constants were increased by 15% and the model was run for 60 years.

Table E-1. No logging scenario.

variable	mean C_{20}	mean Bio_{20}	end Bio_{20}	mean C_{40}	mean Bio_{40}	mean C_{60}	$endB45_{60}$
base	199	285	318	202	311	206	283
B45	205	291	305	206	315	209	288
B25	203	292	324	203	305	199	195
B10	202	290	322	205	316	208	283
B1	199	284	319	202	311	206	283
BS	199	285	318	203	312	206	283
qc	200	285	318	203	311	207	283
qswl	199	285	318	202	311	206	283
qfl	199	285	318	202	311	206	283
fldk	198	285	318	202	311	206	283
swldk	199	285	318	202	311	206	283
ldktoS	199	285	318	203	311	207	283
qcdk	196	285	318	200	311	204	283
qctoS	200	285	318	203	311	207	283
qsoil	202	285	318	205	311	208	283
seflx	197	285	318	200	311	204	283

variable	mean C_{20}	mean Bio_{20}	end Bio_{20}	mean $_{40}$	mean Bio_{40}	mean C_{60}	endB45_{60}
cnvrqc	204	285	318	207	311	210	283
cnvrqswl	199	285	318	203	311	207	283
cnvrqfl	199	285	318	203	311	207	283
LAI45	202	286	317	206	312	210	298
LAI25	201	288	324	202	302	198	211
LAI10	200	287	320	204	315	207	283
LAI1	199	285	321	203	312	207	283
LAIS	199	285	319	202	311	206	283
TR	200	278	282	196	277	194	210
G	201	294	306	203	319	208	279
CD	206	276	272	205	279	203	174
F45	201	294	314	205	322	209	279
F25	198	282	316	200	307	205	283
F10	199	284	319	202	311	206	283
F1	200	287	317	203	313	206	283
FS	201	289	321	204	315	209	283
HD45	201	294	314	205	322	209	279
HD25	198	282	316	200	307	205	283
HD10	199	284	319	202	311	206	283
HD1	200	287	317	203	313	206	283
HDS	201	289	321	204	315	209	283
I	205	293	324	208	310	206	198
K45	193	274	288	192	295	194	281
K25	197	281	311	200	306	202	283
K10	198	283	315	202	310	205	283
K1	199	284	316	202	311	205	283
KS	199	285	318	202	311	206	283
PMAX	206	293	332	213	325	212	218
M	205	293	324	208	310	206	198
C	213	303	341	216	314	216	223

Table E-1 (continued).

variable	mean C_{20}	mean Bio_{20}	end Bio_{20}	mean C_{40}	mean Bio_{40}	mean C_{60}	$endB45_{60}$
PR	213	303	341	215	314	215	223
R	192	274	284	191	293	192	270
SP	199	284	319	202	311	206	283
seedlBio	199	285	319	203	312	206	283
survival	199	285	319	202	311	206	283
mn45	199	284	316	202	312	207	275
mn25	199	284	317	201	309	205	283
mn10	199	284	317	202	310	206	283
mn1	199	284	318	202	311	206	283
mnS	199	285	320	202	311	206	283
mc45	199	282	308	201	309	205	274
mc25	199	285	318	202	311	206	283
mc10	199	285	318	202	311	206	283
mc1	199	284	313	201	308	205	283
mcS	199	284	320	202	311	206	283

Table E-2. Simulations following extraction of 125 m^3 of timber, 20% area with soil disturbance, 40% stand fatally damaged, 20% stand nonfatally damaged.

Variable	$Pioneers_{20}$	mean C_{20}	mean Bio_{20}	end Bio_{20}	$meanC_{40}$	$meanBio_{40}$	$meanC_{60}$	end $B45_{60}$
base	73	101	85	99	103	104	107	98
LAIP	80	104	88	101	104	104	108	98
LAI45	73	100	84	97	101	100	105	100
LAI25	73	101	85	100	105	109	112	108
PmaxP	80	104	88	102	105	105	109	98
Pmax	73	102	86	107	111	118	118	114
MP	75	102	86	100	104	105	108	98
M	73	101	86	104	108	112	115	112
PRP	83	105	89	103	106	106	110	98
PR	73	104	91	117	117	130	127	117
RP	71	101	85	98	101	103	106	98
R	73	100	83	94	95	89	94	82
CD	73	114	109	165	133	146	141	99
CDP	73	103	87	99	103	103	107	98
TR	73	105	91	127	118	129	123	105
BEF[a]	73	100	80	97	104	104	109	107
GP	73	101	85	99	103	105	107	98
C	83	108	95	122	122	132	131	117
i	76	102	87	105	109	113	116	112
K45	70	100	84	96	99	98	102	93
K25	72	100	84	97	101	101	106	98
K10	73	101	85	99	102	104	106	99
K1	73	101	84	99	102	103	106	98
mn45	73	101	85	99	102	103	107	98
mn25	73	101	85	99	103	104	107	98
mn10	73	101	85	99	103	104	107	98
mn1	73	101	85	99	102	103	107	98

Table E-2 (continued).

Variable	$Pioneers_{20}$	mean C_{20}	mean Bio_{20}	end Bio_{20}	$meanC_{40}$	$meanBio_{40}$	$meanC_{60}$	end $B45_{60}$
mnS	73	101	85	99	103	104	107	98
mc45	63	101	85	95	102	103	106	98
mc25	71	101	84	98	103	104	107	98
mc10	72	101	85	99	102	103	107	98
mc1	72	99	83	98	100	102	105	98
mcS	73	101	85	99	103	104	107	98
m_{30}[b]	73	101	85	99	103	104	107	98
ml	73	99	81	93	100	98	104	99
SP	73	99	81	99	103	105	109	98
seedlbio	73	100	83	97	103	104	107	98
survival	73	99	81	99	103	105	109	98
BPS	73	107	86	99	103	104	108	98
NPS	73	102	86	99	103	104	108	98

[a] applied only to trees harvested
[b] pioneer tree mortality rate at 30 years

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BIOGRAPHICAL SKETCH

Michelle was born in Montpelier, Vermont, in 1960 to John Paul and Florence Hebert Pinard. She graduated from Montpelier High School in 1978 and studied wildlife and fisheries biology at the University of Vermont (B.S. 1982). After working for 3 years as a fisheries biologist on the Snake River in Idaho and for 3 years as a high school science teacher in Vermont, Michelle moved to central Florida to study tropical plant ecology in the Department of Botany at the University of Florida. For her master's thesis research, Michelle studied palm population biology in an extractive reserve in Acre, Brazil. After completing this dissertation, Michelle moved to Santa Cruz, Bolivia, where she is working as a forest ecologist for the Sustainable Forest Management Project - BOLFOR.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Francis E. Putz

Francis E. Putz, Chair
Professor of Botany

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

John Ewel

John J. Ewel
Professor of Botany

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Kimberlyn Williams

Kimberlyn Williams
Assistant Professor of Botany

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Wendell P. Cropper Jr.

Wendell P. Cropper
Associate Scientist of Forest Resources and Conservation

This dissertation was submitted to the Graduate Faculty of the Department of Botany in the College of Liberal Arts and Sciences and to the Graduate School and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

December, 1995

Dean, Graduate School